



Grid fault and design-basis for wind turbines - Final report

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Grid fault and design-basis for wind turbines - Final report

Risø-R-Report

Anca D. Hansen, Nicolaos A. Cutululis, Helen Markou, Poul
Sørensen, Florin Iov
Risø-R-1714(EN)
January 2010



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Abstract (max. 2000 char.):

This is the final report of a Danish research project "Grid fault and design-basis for wind turbines". The objective of this project has been to assess and analyze the consequences of the new grid connection requirements for the fatigue and ultimate structural loads of wind turbines.

The fulfillment of the grid connection requirements poses challenges for the design of both the electrical system and the mechanical structure of wind turbines. The development of wind turbine models and novel control strategies to fulfill the TSO's requirements are of vital importance in this design. Dynamic models and different fault ride-through control strategies have been developed and assessed in this project for three different wind turbine concepts (active stall wind turbine, variable speed doubly-fed induction generator wind turbine, variable speed multipole permanent magnet wind turbine).

A computer approach for the quantification of the wind turbines structural loads caused by the fault ride-through grid requirement, has been proposed and exemplified for the case of an active stall wind turbine. This approach relies on the combination of knowledge from complimentary simulation tools, which have expertise in different specialized design areas for wind turbines.

In order to quantify the impact of the grid faults and grid requirements fulfillment on wind turbines structural loads and thus on their lifetime, a rainflow and a statistical analysis for fatigue and ultimate structural loads, respectively, have been performed and compared for two cases, i.e. one when the turbine is immediately disconnected from the grid when a grid fault occurs and one when the turbine is equipped with a fault ride-through controller and therefore it is able to remain connected to the grid during the grid fault.

Different storm control strategies, that enable variable speed wind turbines to produce power at wind speeds higher than 25m/s and up to 50m/s without substantially increasing the structural loads, have also been proposed and investigated during the project. Statistics in terms of mean value and standard deviation have been analysed and rainflow calculations have been performed to estimate the impact over the lifetime of a variable speed wind turbine.

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Preface

This report describes the results of the project titled “Grid fault and design-basis for wind turbines”. The project has been funded by Energinet.dk (project no. 2006-1-6319) and it has been carried out in cooperation between Risø-DTU and Aalborg University.

Risø-DTU (CVR DK 300 60 946) has been responsible for the project.

1 Summary

This is the final report of a Danish research project “Grid fault and design-basis for wind turbines”. The objective of this project has been to assess and analyse the consequences of the new grid connection requirements for the fatigue and ultimate structural loads of wind turbines. The investigation has in particular been focused on fault-ride through (FRT) requirements, whose fulfilment specifies the wind turbines to remain connected to the grid even during and after an abnormal grid voltage is detected.

Currently, as more and more wind power is expected to enter into the electrical network, the power system becomes more vulnerable and dependent on the wind energy production. This increased penetration of the wind power into the electrical network is reflected directly in the grid connection requirements imposed and revised periodically by TSOs all over the world. A survey of the existing grid connection requirements in different countries has been performed and analysed in the present project.

The fulfilment of the grid connection requirements poses challenges for the design of both the electrical system and the mechanical structure of wind turbines. From an electrical point of view, these challenges imply development of advanced controllers for the wind turbines, controllers which are designed and adapted to fulfil different grid requirements, as is for example the fault ride-through requirement. Beside their electrical performance, the design of such controllers also requires a careful investigation on how grid requirements do affect the wind turbines’ structural loads and thus their lifetime. In such investigation, the development of wind turbine models and novel control strategies to fulfil the TSO’s requirements are of vital importance. Dynamic models and control strategies, which have as a task to ensure for wind turbines a fault ride-through operation, have been therefore developed and assessed in the project for three wind turbine concepts:

1. Active stall wind turbine
2. Variable speed doubly-fed induction generator wind turbine
3. Variable speed multi-pole permanent magnet wind turbine

The dynamic performance of the models and of the proposed fault-ride through control strategies has been assessed and emphasized by means of different sets of simulations. The turbine parameters used in the simulations are not linked to a specific manufacturer, but are representative for each turbine and generator type. The simulations performed with the developed models confirm that all the three wind turbine concepts can be controlled to fulfil fault ride-through operations. It has been shown that the fault ride-through capability of an active stall wind turbine is directly dependent on the ability of the turbine to reduce its mechanical power by pitching quickly the blades during the grid fault. In the case of variable speed wind turbines, the fault ride-through capability is enhanced and facilitated by the presence of power electronics, with special focus on the damping of the torsional oscillations in the drive train during grid faults and on some frequency converter protection issues.

A computer approach for the quantification of the structural loads of the wind turbine caused by the fault ride-through grid requirements, has been proposed and exemplified in the project for the case of an active stall wind turbine. This approach relies on the combination of knowledge from complimentary simulation tools, such as the advanced aeroelastic computer code HAWC2 and the dedicated power system simulation tool DIgSILENT. These tools have expertise in different specialised design areas for wind turbines and are used intensively by the wind energy industry at the moment. The wind turbine loads are thus simulated and analysed in HAWC2, while the wind turbine electrical interaction with the grid during grid faults is assessed in DIgSILENT.

In order to quantify the impact of grid requirements on the wind turbines structural loads and thus on their lifetime, a rainflow and a statistical analysis for fatigue and ultimate structural loads, respectively, have been performed and compared for two cases, i.e. one where the turbine is immediately disconnected from the grid when a grid fault occurs and one where the turbine is equipped with a fault ride-through controller and

therefore it is able to remain connected to the grid during the grid fault. The investigation has in particular been focused on the analysis of structural loads on tower and blades. A three phase short circuit fault with duration of 100ms has been considered in the case studies. The different investigations performed in this respect during the project have shown that the fulfilment of the fault ride-through requirement does not have any significant impact on structural loads, like blade flap moment, blade edge moment, tower top tilt moment, tower top yaw moment, tower bottom tilt moment, tower bottom side moment and shaft bending moment. This conclusion is based on a set of comparisons performed for an assumed fault occurrence of 50, 500 and 3000 in a 20 year lifetime of an active stall wind turbine. The extreme case of 3000 fault occurrences in 20 years has been based on feedbacks received during the project from developers in India, for whom such a high occurrence of grid faults is to be expected. This conclusion, that neither the fatigue nor the ultimate structural loads on the tower and the blades of a turbine are affected by the fulfilment of the fault ride-through requirement, has been assessed for an active stall wind turbine. In the authors' opinion, this would also be expected in the case of the variable speed turbine as in these configurations, the mechanical part of the turbine is partially or even fully isolated from the grid due to the presence of power converters and their control. In these configurations, the turbine itself may be relatively immune to grid faults from a structural point of view. For example, for the case of variable speed multi-pole permanent magnet wind turbine, the power converter decouples completely the generator from the grid, and therefore the wind turbine system is not directly subjected to grid faults, which is contrary to the direct grid connected wind turbine generators, as it is the case of active stall wind turbines.

The importance of continuing production of wind turbines in high winds to ensure a reliable and robust energy production has also been in focus of the present research work. Different control strategies, that enable variable speed wind turbines to produce power at wind speeds higher than 25m/s and up to 50m/s without substantially increasing the structural loads, have been proposed and investigated. A set of load cases for wind speeds from 4m/s to 50m/s with turbulence intensities according to IEC61400-1 rev 3 class IA has been performed in order to calculate the increase in fatigue damage when allowing the turbine to run in storm conditions. Statistics in terms of mean value and standard deviation have been analysed and rainflow calculations have been performed to estimate the impact over the lifetime of a variable speed wind turbine.

2 Background

Wind energy is one of the fastest growing industries nowadays. The increased penetration of wind energy into the power system over the last years is directly reflected in the wind turbines grid connection requirements [1], which are continuously subjected to increased periodic revisions. These grid requirements require wind turbines to behave similarly to conventional power plants. Especially the requirements for wind turbines to stay connected to the grid during and after a voltage sag (i.e. fault ride-through requirements), pose potential challenges in the design of wind turbines.

Over the last years, these challenges have initiated different research activities with focus on the development of advanced wind turbines controllers, suitable to ensure wind turbines to fulfil the grid requirements. Beside their electrical performance, the design of such controllers also implies an understanding of their influence on the wind turbines' structural loads.

Nowadays, there is a lack in long-term experience concerning the quantification of the grid faults' impact on the structural loads, as up to now, this issue has not been sufficiently investigated in the relevant literature. There is therefore no clarified knowledge on how the grid faults and the fulfilment of the new grid requirements, especially of the fault ride-through (FRT) requirement, affect the structural loads of wind turbines. The reason is that at the moment, the design of wind turbines take place in specific dedicated simulation tools, which are specialised either in the mechanical design area or in the electrical design area, regarding grid integration issues of wind turbines. The expertise in these wind turbine design areas is built-up independently, with very

specific focus and without any influence from one design area to another. For example, grid faults are typically simulated in dedicated power system simulation tools, which, as they are using simplified mechanical models, are not able to provide a thorough insight on the structural loads. On the other hand, wind turbine structural loads are typically assessed in advanced aeroelastic computer codes, which by applying simplified electrical models do not provide detailed electrical insight. In order thus to be able to analyse the grid faults' impact on the wind turbine structure, it is important to assess properly the interplay between the electrical and the mechanical aspects of the wind turbine response during grid faults. This fact means that it is necessary to be able to combine the knowledge from simulation tools with complimentary abilities.

Another area, where the study of the structural loads needs more research, is that related to wind turbines operation during wind storms. Wind turbines typically operate between a cut-in wind speed of 3-4m/s and a cut-out wind speed of 25m/s. This operational range is defined based on lifetime cost optimization criteria for the turbine. The overall power production during operation at above cut-out wind speeds is thus limited, and does not compensate for the higher loads experienced by the turbine at these wind speeds; i.e. the turbine is not designed to withstand these higher loads. In cases of storms passing through, the wind turbines typically shut-down in order to avoid high structural loads. However, due to high penetration of wind energy into the electricity grid, there is a keen interest from the grid companies to ensure a reliable and robust energy production also in storm situations, to keep the wind turbines on-line during a storm passing through, even if they are forced not to run at rated power output. To the best of our knowledge, work on incurring loads from storm reduction control strategies has not been published. Enercon have implemented a storm control strategy on their turbines, in which the rotational speed is reduced above the cut-out wind speed. However, as there is not much available information about it, there is a major need for investigations and publications in this respect.

3 Objective

The objective of this project has been to assess and analyse the consequences of the new grid connection requirements for the fatigue and ultimate structural loads of wind turbines [2]. The investigation has in particular been focused on fault-ride through (FRT) requirements, whose fulfilment specifies the wind turbines to remain connected to the grid even during and after an abnormal grid voltage is detected. Practical experience shows that there is a need for such investigations. The grid connection requirements for wind turbines have increased significantly during the last 5-10 years. Especially the requirements for wind turbines to stay connected to the grid during and after voltage sags, imply potential challenges in the design of wind turbines. These requirements pose challenges for the design of both the electrical system and the mechanical structure of wind turbines.

Another objective of this work has been to investigate possible alternative and additional control strategies, which enable wind turbines to produce power even in storm operation situations in the conditions that their fatigue and extreme loads are kept within a reasonable level, compared to the fatigue and extreme loads experienced within the normal operational wind speeds.

The report is organized as follows. First a mapping of the grid faults and the fault ride-through capability requirements in different countries is presented. The work regarding the development of the dynamic models and fault ride-through control strategies for three different wind turbine concepts (active stall wind turbine, variable speed doubly-fed induction generator wind turbine, variable speed multipole permanent magnet wind turbine) is then presented and assessed. The report focuses then on the grid faults and on the fault ride-through requirement impact on structural loads, like blade flap moment, blade edge moment, tower top tilt moment, tower top yaw moment, tower bottom tilt moment, tower bottom side moment and shaft bending moment. Different storm control strategies, that enable variable speed wind turbines to produce power at wind speeds higher than 25m/s and up to 50m/s without substantially increasing the

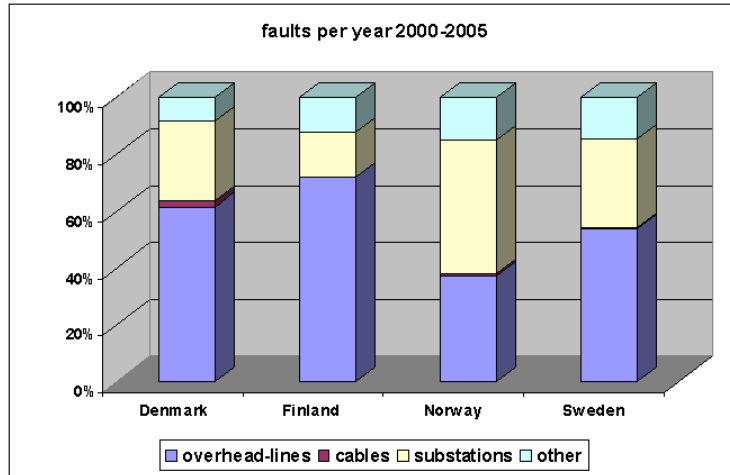


Figure 1: Types of faults in the Nordic countries transmission system – source [1].
structural loads, are also proposed and investigated. Statistics in terms of mean value and standard deviation have been analysed and rainflow calculations are performed to estimate the impact over the wind turbines lifetime.

4 Overview of grid faults and grid requirements

In order to evaluate the grid faults and grid requirements impact on wind turbine structural loads, it is necessary to perform an overview on the grid faults types, on their frequency and on the grid requirements in different countries.

4.1 Grid faults

Wind turbines connected to the grid are frequently subjected to grid faults. Various grid faults can occur in the electrical networks and most of them are related with the network voltage. They are usually characterised by a change in the magnitude of the voltage and by time duration.

Such a mapping of the grid faults in different countries is provided in details in [1]. In this report, statistics regarding, for example, the grid faults in the transmission system of the Nordic countries (Denmark, Finland, Norway and Sweden), are presented and analysed. Figure 1 illustrates for example that, in the Nordic countries excepting Norway, the most faults per year are located on overhead lines in the period 2000-2005.

According to the investigation presented in [1], in the Nordic countries except Norway, the most faults per year in the period 2000-2005 are located on overhead lines, while the number of faults located in cables is less than 2.5% of the total number of faults. Furthermore, in these Nordic countries, most of the faults on overhead lines in the period 1996-2005 are located on 132kV lines, while 400kV lines are less susceptible to faults. The analysis in [1] reveals also that, in Nordic countries, the single phase fault type has the highest probability to occur compared with other fault types, as illustrated in Figure 2. Nevertheless, different investigations presented in [1], indicate that three phase grid faults may however have the biggest impact on the wind turbine mechanical system.

4.2 Grid requirements

The connection of large wind turbines to the grid has a large impact on grid stability. The increased penetration of wind energy into the power system over the last decade has therefore led to serious concern about its influence on the dynamic behavior of the power system. It has resulted in the power system operators revising and increasing the grid connection requirements in several countries.

Basically, the grid codes, which cover a wide range of voltage levels from medium voltage to very high voltage, require wind turbines to have an operational behavior more similar to that of conventional generation capacity and more responsibility in network operation. The status of wind turbines is thus changing from being simple energy sources to having power plant status. This means that sooner or later, they will have to share some of the duties carried out today by the conventional power plants, namely behave as active controllable components [3] in the power system, i.e. regulating active and reactive power and performing frequency and voltage control on the grid. These requirements have focus on power controllability, power quality, fault ride-through capability and grid support during network disturbances.

A detailed overview of the national grid requirements in countries as Denmark, Ireland, Germany, Great Britain, Spain, Italy, USA and Canada is also provided in [1]. The most common issue addressed in these grid requirements address power control

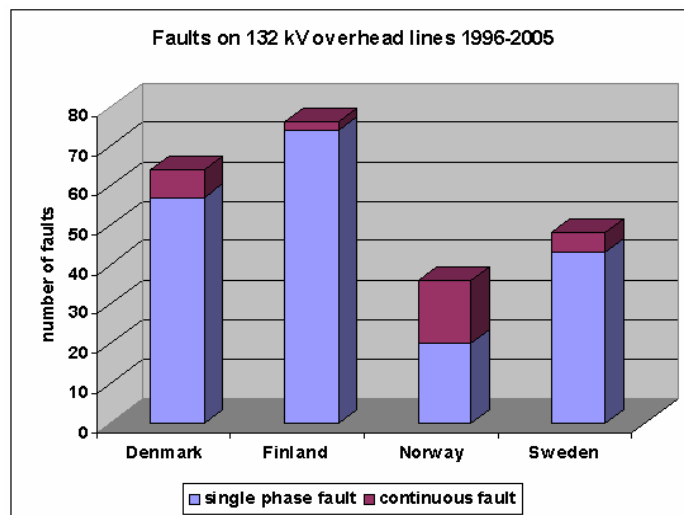


Figure 2: Frequency of different fault types on 132kV overheads lines – source [1]. capabilities and fault ride-through capabilities of large wind farms.

Power control capability

The power control capability means mainly that the wind turbines have to share, for shorter or longer periods, some of the duties carried out traditionally by conventional power plants, such as regulating active and reactive power and performing frequency and voltage control on the grid.

Curtailment of produced power based on system operator demands is mandatory in Denmark, Ireland, Germany and Great Britain [1].

Currently, Denmark has the most demanding requirements regarding the controllability of the produced power. Wind farms connected at the transmission level shall act as a conventional power plant providing a wide range of controlling the output power based on Transmission System Operator's (TSO) demands and also participation in primary and secondary control [4]. Different active power regulation functions are required in the wind farm control and some of them are shortly in Figure 3, as delta control, balance control, absolute production and system protection.

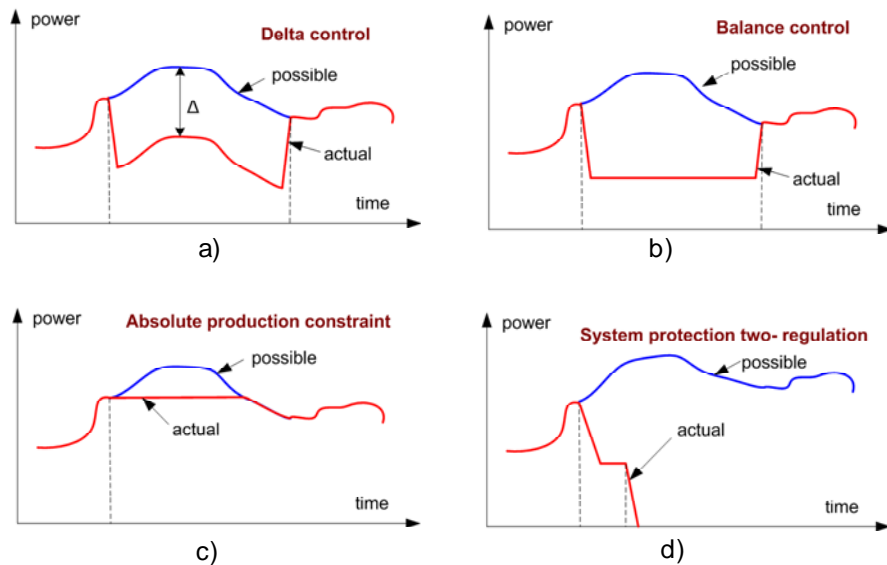


Figure 3: Regulation function for active power implemented in the wind farm controller required by the Danish grid code: a) delta control, b) balance control, c) absolute production constraint and d) system protection [4]

Fault ride-through capability

The fault ride-through requirement has been imposed in order to avoid significant loss of wind turbine production in the event of grid faults.

Up to 7-8 years ago, wind turbines were only required to disconnect from the grid when a grid fault was detected, in order to avoid large inrush currents when the voltage recovered. However, with the increased capacity of wind power in the power system over the years, such a disconnection of wind turbines could generate problems in the control of frequency and voltage in the system, and as worst case a system collapse. The increased penetration of wind energy into the power system over the last decade has therefore led to serious concern about its influence on the dynamic behaviour of the power system. It has resulted in the power system operators revising and increasing the grid connection requirements in several countries.

The fault ride-through capability addresses primarily the design of the wind turbine controller in such a way that the wind turbine is able to remain grid-connected during grid faults. The fault ride-through demand is also a challenge on how to recover the voltage after a grid fault. This is especially the case of wind turbines with squirrel cage induction generators (SCIG) which, by being kept connected to the grid during grid faults may require large currents to energize their induction generators, when the voltage returns after a while. This can lead to possible violation of grid codes and security standards.

A summary of the fault ride-through requirements in different national grid codes is given in [1] and presented and illustrated in Table 1 and Figure 4, respectively. Notice that some national grid codes e.g. Denmark and Ireland have specific fault ride-through requirements for distribution networks as well as for transmission ones, while other national grid codes have focus only on the transmission level. The voltage profiles in these national requirements are given specifying the depth of the voltage drop and the clearance time as well. In some of the grid requirements, as in Denmark, Ireland and Germany, the definition of the voltage profile is clearly specified regarding the type of the fault, i.e. symmetric or asymmetric.

Table 1: Summary of national fault ride-through requirements - source [1].

Country	Voltage Level	Fault ride-through capability				
		Fault duration	Voltage drop level	Recovery time	Voltage profile	Reactive Current injection
Denmark	DS	100 msec	25%U _r	1 sec	2, 3-ph	no
	TS	100 msec	25%U _r	1 sec	1, 2, 3-ph	no
Ireland	DS/TS	625 msec	15%U _r	3 sec	1, 2, 3-ph	no
Germany	DS/TS	150 msec	0%U _r	1.5 sec	Generic	Up to 100%
Great Britain	DS/TS	140 msec	15%U _r	1.2 sec	generic	no
Spain	TS	500 msec	20%U _r	1 sec	generic	Up to 100%
Italy	> 35 kV	500 msec	20%U _r	0.3 sec	generic	no
USA	TS	625 msec	15%U _r	2.3 sec	generic	no
Ontario	TS	625 msec	15%U _r	-	-	no
Quebec	TS	150 msec	0%U _r	0.18 sec	Positive sequence	no

Notice that there is a significant span in the fault ride-through requirements in different countries. For example, the fault duration varies from 100 msec (in Denmark) to 625 msec (in Ireland, USA and Canada), while the voltage drop level down varies between 25% to even 0% of the nominal value. The Ireland's code is very demanding regarding the fault duration, while Denmark has the lowest fault duration with only 100msec. However, Denmark's code requires the wind turbine to remain connected to the grid during successive faults. The German grid code requires the wind turbines to remain connected to the grid during voltage sags down to 0% from the rated voltage in the Point of Common Coupling (PCC) for duration of 150msec. Moreover, a reactive current injection up to 100% during fault is required, this requirement being also present in the Spanish grid code.

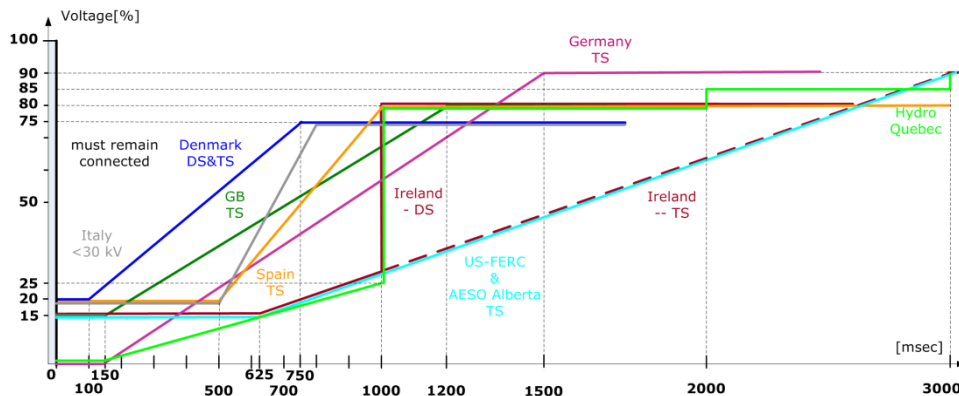


Figure 4: Review of fault ride through requirements for wind power in European grid codes [5]

4.3 Wind turbine loads and certification standards

The design basis analysis of wind turbine loads and lifetime includes typically the distribution of fatigue loads and extreme loads for normal, start and shut-down operations. However, besides these aspects, it could also be relevant to know which is the impact of grid requirements on the wind turbine structural loads compared to those corresponding to standard shut-down operations.

Nowadays, the continuous increase of wind turbine size and of wind energy penetration level into power networks, makes the presence of an advanced controller to

become crucial in order to ensure fulfilment of the grid requirements and thus a better power system operation. Significant research has been and is currently done to develop advanced fault ride-through controllers. Nevertheless, the design of such advanced control schemes, that enable wind turbines to fulfil the grid requirements, requires a better understanding on the effects on the wind turbines loads, as no clarified knowledge and investigations on how the fulfilment of the new wind turbine grid codes affects the structural loads exists.

Grid faults are basically experienced by the wind turbine as changes in the voltage at the generator terminal. This causes typically transients in the generator electromagnetic torque, which result in significant stress of the wind turbine mechanical system and may also have a detrimental effect on the drive train components, such as the gearbox. Practice experience indicates that grid faults have an impact on drive train loads, but the impact on tower and blades structural loads might also have a high relevance. The attention in this work is therefore directed toward these structural loads, caused during fault ride-through operation, in order to provide a more complete understanding of the loads distribution during the whole wind turbine lifetime.

One should have in mind that the fast development of the wind energy industry implies a continuous revision not only of the grid connection requirements, but also of the certification standards. These standards have to specify the essential wind turbine design requirements to ensure the engineering integrity of wind turbines. They are at the moment not updated according to the progress of technology, knowledge and new grid connection requirements. IEC 61400-1 certification standard, (paragraph 7.4) [6], presents for example a list with different design situations and load cases (i.e. faults during normal or parking operation). Loss of the electrical power network, voltage/frequency ranges, voltage unbalance are specified, but not really dealt with in certification. IEC 61400-1 certification standard stipulates the wind turbines to be designed to withstand electrical faults and any other type of abnormal operating conditions that may occur in the grid, but it does not state requirements in terms of specific faults to be considered, leaving this task to the designer and the certifier of the wind turbine.

4.4 Conclusions

Currently, more grid operators are changing the interconnection requirements for wind power, especially for the transmission systems. This is an obvious signal that more wind power will enter into the electrical system in the near future. These requirements in most of the cases are specifically addressed to the ride-through capabilities of wind power installations. According to these demands a wind turbine/farm must withstand short circuits with different voltage drops and recovery times.

The impact of emerging new grid connection requirements on wind turbines is an important grid integration issue in the future. The survival of different wind turbine concepts and controls is strongly conditioned by their ability to comply with stringent grid connection requirements, imposed by utility companies. Beside its impact on the mechanical design and control of wind turbines, the grid integration aspect has also an effect on wind turbines' role in the power system, on wind turbine technologies' survival on the market, as well as on the wind turbines' loads.

5 Wind turbines modelling and control during grid faults

This chapter underlines the most important modelling and the control issues, which have been developed and implemented, regarding fault ride-through control capability for three different wind turbine concepts, namely:

- Active stall wind turbine
- Doubly-fed induction generator wind turbine
- Multipole permanent magnet synchronous generator wind turbine.

As the normal operation approach have been plenty discussed and published [7], [8], [9], only grid fault operation is in the attention of the present work.

Basically, the modelling and control issues of these wind turbine concepts are similar, but differ internally due to the different system configurations. As well known, the general model of a wind turbine, no matter concept, comprises different sub-models, as a wind model, an aerodynamic model, a mechanical model, an electrical model and a controller model.

As the wind model, the aerodynamic model and the mechanical model are general and applicable for all these three wind turbines concepts, their issues are shortly presented in the following. On the other hand, as the electrical model and the controller model depend strongly on each wind turbine concept configuration, they are specifically addressed in the following sections.

In grid fault dynamic impact studies, the wind speed is typically assumed constant during the observed time frames, as the fault operation is small compared to the wind speed fluctuations.

The aerodynamic model contains the aerodynamic properties of the wind turbine blades. A simplified aerodynamic model is typically used based on a two dimensional aerodynamic torque coefficient C_q table provided by a standard aerodynamic program [8].

In stability analysis, when the system response to heavy disturbances is analysed, the drive train system, which is the only mechanical part having significantly influence on the power quality, must be approximated by at least a two-mass model [7]. The idea of using a two-mass mechanical model is to get a more accurate response from the wind turbine during grid faults and to have a more accurate prediction of the impact on the power system. The mechanical model used in the present context is therefore a two-mass mechanical model, connected by a flexible shaft characterized by a stiffness k and a damping c , as described in [8]. The stiffness and damping components are modelled on the low-speed shaft, while the high-speed shaft is assumed stiff. Moreover, an ideal gear with the exchange ratio $1: n_{gear}$ is included. One mass represents the turbine inertia J_{rot} , while the other mass is equivalent to the generator inertia J_{gen} . The motion equations on the low and high speed shaft of the turbine are:

$$\begin{aligned} J_{rot} \dot{\omega}_{rot} &= T_{aero} - T_{shaft} \\ J_{gen} \dot{\omega}_{gen} &= T_{mec} - T_{el} \end{aligned}$$

where $T_{mec} = T_{shaft} / n_{gear}$. The aerodynamic torque from the rotor acts on one end of the drive train, while the mechanical torque from the generator side acts on the other end of the drive train. The result of this is torsion of the shaft. In steady state, all torques are in equilibrium, i.e. $T_{aero} = T_{shaft}$ and $T_{mec} = T_{el}$.

During grid faults the electrical torque is significantly reduced and therefore the drive train system acts like a torsion spring that gets untwisted. Owing to the torsion spring characteristic of the drive train, both the mechanical torque, aerodynamical torque, and thus the generator speed, start to oscillate with the so-called free-free frequency:

$$f_{osc} = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{J_{eq}}}$$

where J_{eq} is the equivalent inertia of the drive train model determined by:

$$J_{eq} = \frac{J_{rot} \cdot n_{gear}^2 \cdot J_{gen}}{J_{rot} + n_{gear}^2 \cdot J_{gen}}$$

As the electrical model and the controller model depend specifically on each wind turbine concept configuration, they are in the following addressed for each individual wind turbine concept, with special focus directed to the control issues in particular related with fault-ride through capability requirement.

5.1 Active stall wind turbine

The system configuration and control of an active stall wind turbine is sketched in Figure 5. The modelling of active stall wind turbines (ASWT) has been addressed in a variety of publications [7-11].

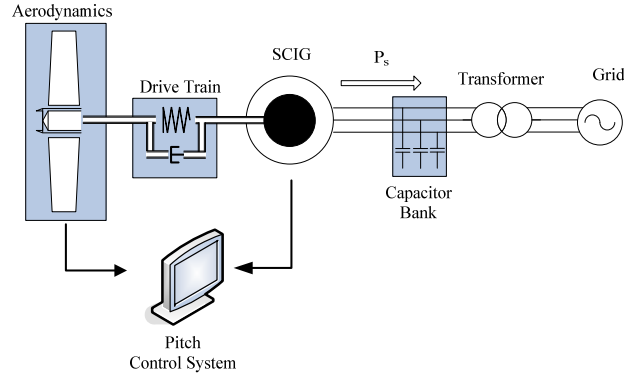


Figure 5: System configuration and control of the ASIG wind turbine.

As well known, in case of normal operating conditions i.e. production cases from cut-in to cut-out wind speeds, the wind turbine has either to produce maximum power (e.g. in power optimisation mode) or to limit its production to its rated power (e.g. in power limitation operation mode).

Figure 6 illustrates the pitch controller of the active stall wind turbine in normal operating conditions. Notice that, the controller, described in details in [11], enables a fast control of the wind turbine powers through the pitch angle both in the power optimization and power limitation mode. The controller is designed generically in a parametric way, thus its performance can be adjusted to specific wind turbines dimensions.

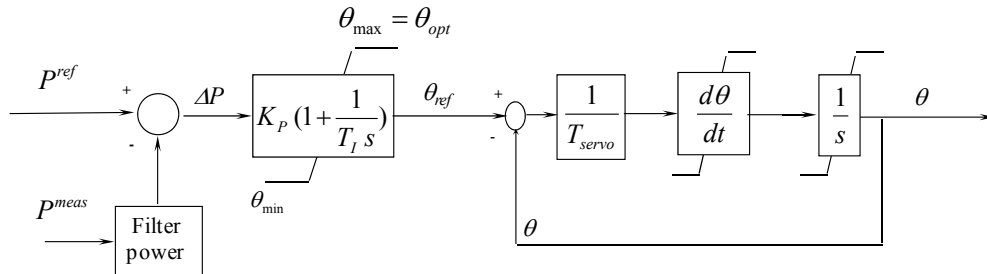


Figure 6: Normal operation condition pitch controller of the active stall wind turbine.

In the power optimization mode, when the power from the wind is less than the nominal power, the error through the controller is positive. This is integrated up until the pitch reference reaches the upper limit of the controller, which is chosen to be the optimal pitch. In the power limitation mode, the power error of the controller becomes negative and therefore the pitch angle is moving out the upper limitation and starts actively to control the power.

In case of fault operation condition, the fault ride-through capability of an active stall wind turbine, and thus its stabilization during a grid fault, can be achieved by reducing the wind turbine power production for duration of few seconds from the moment of fault occurrence [7], [12]. The ordering of power reduction is given for example when the monitoring of the grid voltage indicates a fault occurrence.

In this work, the ASWT control strategy during grid faults is implemented based on [10], [12]. The idea is that during the fault, the normal operation condition controller, shown in Figure 6, is switched off and replaced by an open loop fault operation controller, which reduces directly the mechanical power of the rotor to a predefined level by pitching quickly the blades. This is done in order to prevent wind turbine from going

overspeed and to assist thus in voltage recovery. Notice that fault ride-through capability implies that the active stall wind turbine has to change its pitch angle as quickly as possible (maximum pitch rate).

When the grid fault is cleared and the voltage has recovered, the wind turbine continues running at the reduced power for still few seconds, after which it starts to ramp up the mechanical power of the rotor and to re-establish the normal operation conditions control of the wind turbine [12].

The use of the active stall wind turbines control temporarily to reduce the mechanical power of the rotor by pitching the blades provides fault ride-through capability and thus a stable operation for active stall wind turbines during grid faults. Beside this, such control contributes both to voltage re-establishment in the grid, where active stall wind turbines are connected to during grid faults, and to the reduction of the capacity demands of dynamic reactive compensation.

5.2 Doubly-fed induction generator wind turbine

The doubly-fed induction generator wind turbine configuration (DFIG), which stands nowadays as the mainstream configuration for large wind turbines [13], is illustrated in Figure 7. To ensure a realistic response of a DFIG wind turbine, the main electrical components as well as the mechanical parts and the controllers have to be considered in the model. In this work, the DFIG normal operation control strategy has been implemented according to the work described in [14].

Figure 7 illustrates the control and protection of DFIG wind turbine system configuration, which is essential for an effective behaviour of a DFIG wind turbine during both normal and grid fault operations. It contains:

- Wind turbine itself with the drive train, the aerodynamics and the pitch angle control system
- DFIG protection and control system during grid faults

In normal operation, the rotor side converter (RSC) controls the active and reactive power delivered to the grid through the stator, while the grid side converter (GSC) ensures nominal voltage at the common DC-bus at unity power factor operation of the converter.

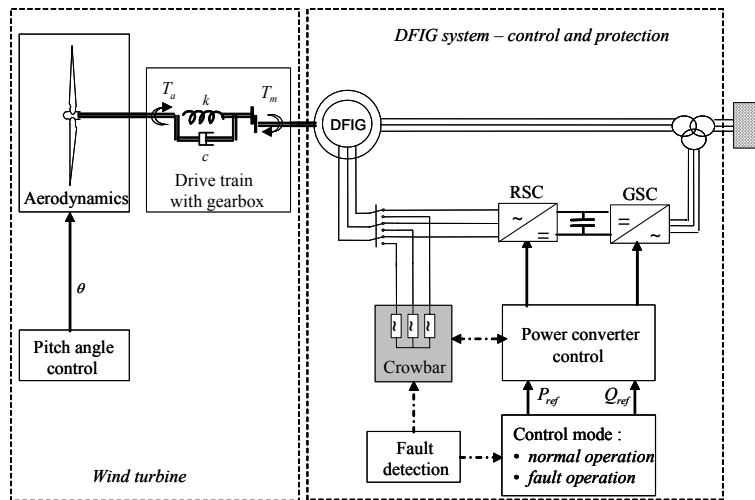


Figure 7: DFIG wind turbine protection and control block diagram during grid faults.

In the case of grid faults, which are in focus in the modelling and control of wind turbines in the present report, the controllability of DFIG variable speed wind turbines embraces both the wind turbine control for preventing over-speeding of the wind turbine and the control and protection of the power converter during and after grid faults.

The wind turbine control system consists of a pitch controller and an electrical control of the converters. As illustrated in Figure 8, the pitch controller is realized by a

PI controller with antiwind-up, using a servomechanism model with limitation of both the pitch angle and its rate-of-change. A gain-scheduling control of the pitch angle, as described in [14], is implemented in order to compensate for the non-linear aerodynamic characteristics.

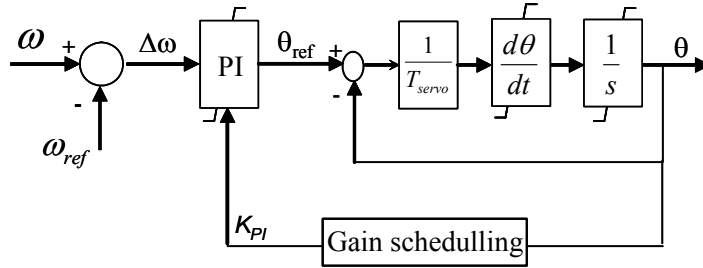


Figure 8: Pitch angle control.

As the pitch angle controls directly the generator speed to its reference signal, this control is able to prevent over-speeding both in normal operations and during grid faults, by limiting the mechanical power extracted from the wind and thus restoring the balance between electrical and mechanical power. This means that there is no any need to design another pitch control solution additional to the one sketched in Figure 8, in order to improve the dynamic stability during grid faults. This is, for example, the case in [15] and [16], where the reduction of the aerodynamic power and the prevention of the overspeeding during grid faults are realised by implementation of an additional pitch control solution.

The control of the electrical system of the DFIG wind turbine during grid faults is depicted in Figure 9. Notice that the decoupled control of active and reactive power is applied through vector control techniques [17], which allows for changes in the active and reactive power in the range of milliseconds.

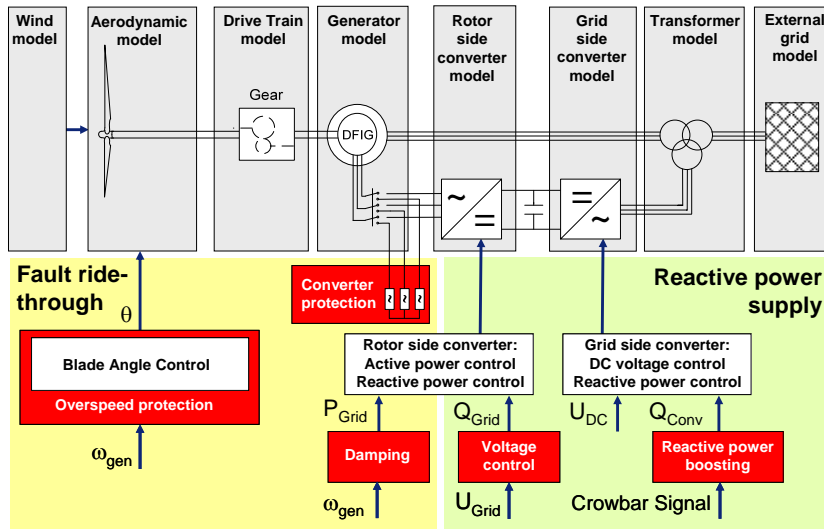


Figure 9: Generic control strategy for DFIG wind turbine during grid faults.

The specific converter arrangement in the DFIG wind turbine configuration requires an advanced protection system, because high transient currents and voltages can arise in the generator during grid faults [18]. The protection of the converter against overcurrents, but also of the generator rotor and the dc-link against overvoltages is typically ensured via the so-called crowbar. In principle, the crowbar is external rotor impedance, coupled via the slip rings to the generator rotor. When the crowbar is triggered, the rotor side converter is disabled and bypassed, and therefore the independent controllability of active and reactive power is temporary lost. Nevertheless,

the crowbar guarantees, that the wind turbine can stay connected to the grid and can thus directly contribute to power production, when the fault is cleared. Since the grid side converter is not directly connected to the generator windings, where the high transient currents occur, this converter is not blocked by the protection system during grid faults. When the crowbar is removed, the RSC is enabled again to control independently the active and reactive power.

In normal operation of a DFIG wind turbine, the active power reference for the rotor side converter is given by the maximum power tracking (MPT) point characteristic as function of the optimal generator speed, [14]. In the case of a grid fault, this power reference is defined as the output of a damping controller [8]. During a grid fault voltage and power at the wind turbine terminal drop and thus the power in the DFIG drops, too. This results in an acceleration of turbine and generator. As mentioned before, in case of a grid fault the blade angle control serves also as an overspeed protection. Moreover, when the electrical power drops the drive train will start to oscillate. Due to this reason a damping controller has been implemented in order to actively damp any torsional oscillations of the drive train. Such damping controller prevents instability of the system and substantially reduces the mechanical stresses of the turbine. It ensures thus the fault ride-through capability of the wind turbine, i.e. avoids an eventual wind turbine grid disconnection due to undamped oscillations in the generator speed.

Notice that the pitch control system is not able to damp the torsional oscillations, because of several delay mechanisms in the pitch. The pitch control damps the slow frequency variations in the generator speed, while the damping controller is able to damp the fast oscillations in the generator speed.

Figure 10 illustrates the effect of the damping controller for the example of a case, where a 100ms three phase fault appears at the high voltage terminal of the 3-windings transformer of a 2MW DFIG wind turbine. It is assumed that the wind turbine runs at its rated power at the fault instant. The generator speed and the mechanical torque of the DFIG wind turbine are illustrated for the situations with and without damping controller, respectively.

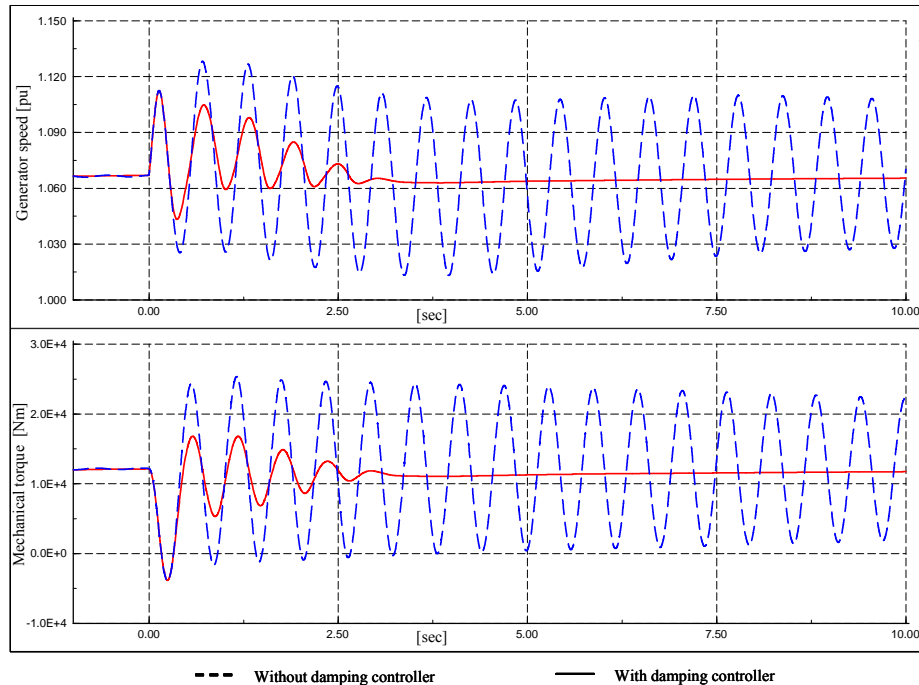


Figure 10: Damping controller effect.

Note that without damping controller the torsional oscillations excited by the grid fault are only slightly damped still 10 s after the grid fault incident. It is clearly visible that the oscillations are quickly damped over a few seconds, when the damping controller is used. Furthermore the amplitude of the mechanical torque oscillations is

much smaller when using the damping controller. Moreover, in contrast to the case when no damping controller is used, the mechanical torque crosses only once through zero when the damping controller is used, and therefore the mechanical stress of the drive train is substantially reduced in this case. The damping controller is thus minimizing the grid fault effect on both the mechanical and the electrical side of the turbine. The protection system together with the damping controller enhances thus the DFIG fault ride-through capability.

The use of a crowbar protection, a damping controller and a proper coordination between frequency converters controllers enhance thus the fault ride-through and the voltage grid support capability of DFIG wind turbines during grid faults.

5.3 Multi-pole permanent magnet synchronous generator wind turbine

A typical configuration of a variable speed wind turbine based on a multipole permanent magnet synchronous generator (PMSG) and full-scale converter is illustrated in Figure 11. It consists of:

- Wind turbine mechanical level, i.e.:
 - Aerodynamics
 - Gearless drive train
 - Pitch angle control
- Wind turbine electrical level, i.e.:
 - Multipole permanent magnet synchronous generator (PMSG)
 - Full-scale frequency converter and its control

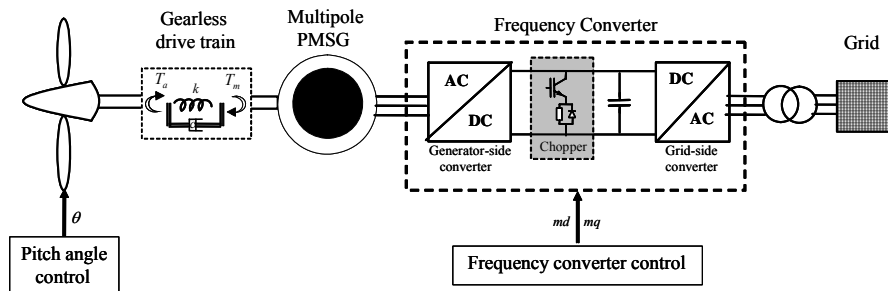


Figure 11: Variable speed multiple PMSG wind turbine configuration.

As illustrated in Figure 11, the aerodynamic rotor of such wind turbine configuration is directly coupled to the generator without any gearbox, i.e. through a gearless drive train. The synchronous generator is connected to the grid through a full-scale frequency converter system, which controls the speed of the generator and the power flow to the grid. The permanent magnets are mounted on the generator rotor, providing a fixed excitation to the generator. The generator power is fed via the stator windings into the full-scale frequency converter, which converts the varying generator frequency to the constant grid frequency. The full-scale frequency converter system consists of a back-to-back voltage source converter (generator-side converter and the grid-side converter connected through a DC link), controlled by IGBT switches.

Notice that a multi-pole PMSG wind turbine is connected via a full-scale frequency converter to the grid and therefore, in principle, can easily accomplish fault ride-through and support the grid during faults. The presence of the full-scale converter makes it possible for this wind turbine configuration to absorb or produce large amounts of reactive power especially during grid faults. As the converter decouples the generator from the grid, the generator and the turbine system are not directly subjected to grid faults in contrast to the direct grid connected wind turbine generators.

The control of the PMSG's electrical system, proposed and implemented during this project, has been described in details in [19] and therefore it is shortly presented in the following. As illustrated in Figure 12, it is modelled on a generic level, without focusing

on any particular design of a manufacturer. The generator side converter controls the DC-link voltage and the stator voltage of the generator, while the grid side converter is used to control the active and reactive power supply to the network. Notice that, as the generator side-converter is not directly connected to the grid, it is able to fulfil its task to control the DC-link voltage undisturbed during faults. Contrary, the grid-side converter is directly affected by grid fault and it cannot therefore deliver the expected active power, when it is subjected to low voltage during faults. The generator-side converter starts then to reduce the generator power by decreasing the stator current in order to keep the DC-link voltage constant. The power surplus is transformed in rotational energy of the rotor mass, which starts to accelerate. If the speed exceeds the rated value, the pitch controller acts to limit the speed. Similar to the control of DFIG wind turbines [8], the control of the power converter in this wind turbine configuration is also based on two control loops in cascade: a very fast inner current controller regulating the currents to the reference values that are specified by the outer slower power controller.

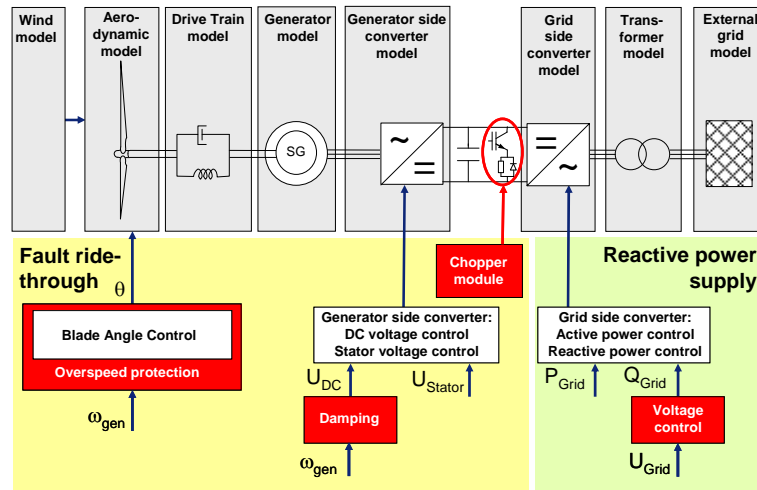


Figure 12: Generic control strategy for PMSG wind turbine during grid faults.

The fault ride-through capability of multi-pole permanent magnet wind turbines is facilitated and enhanced by using a pitch controller, a damping controller and eventually a chopper. The pitch control, illustrated in Figure 8, serves again as an overspeed protection. The chopper, placed in parallel to the capacitor in the DC-link, is typically used to burn the surplus power. The damping controller acts similar to a power system stabilizer [20], is therefore implemented as described in details in [19]. The reason for using such damping controller is that, a multipole PMSG wind turbine with full-scale converter has no inherent damping. This implies that any small speed oscillation excited by mechanical or electrical load changes, can be amplified causing self-excitation, high mechanical stress of the drive train and even instability if no external damping controller is applied. Its goal is therefore to influence the generator electrical torque in such a way that it counteracts the speed oscillations and ensures a stable operation of the wind turbine. As result, it damps the torsional oscillations in the drive train during faults, owing to the torsional spring behaviour of the system following the sudden loss of electrical power.

Figure 13 illustrates the effect of the damping controller on the multipole PMSG wind turbine with full-scale converter, when the system gets excited e.g. by a sudden change in the wind speed from 12m/s down to 11m/s. The wind speed, the generator speed and the active power production are illustrated for the situations with and without damping controller respectively. Notice that without the damping controller, the wind speed change provokes large oscillations with increased amplitude in the generator speed, the system becoming unstable. It is clearly visible that these oscillations are quickly damped when the damping controller is used. Such a damping system ensures thus a stable operation of the multipole PMSG with full-scale converter configuration,

which otherwise can easily become unstable whenever there is a sudden change in the system.

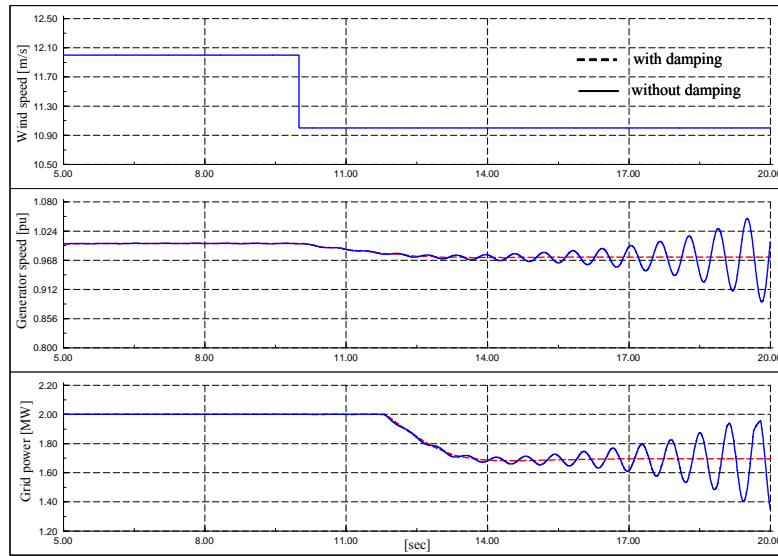


Figure 13: The performance of the PMSG wind turbine with and without damping controller, in case of a change in wind speed from 12m/s to 11 m/s.

In contrast to the DFIG wind turbine, no converter protection is necessary. As the generator of the PMSG wind turbine is decoupled from the grid by the converter, no transient currents and thus no damaging risk for the converter arise.

The control strategy for the full-scale converter, developed and implemented during this project, is an alternative one, different from a traditional one. Figure 14 points out the differences between these two control strategies.

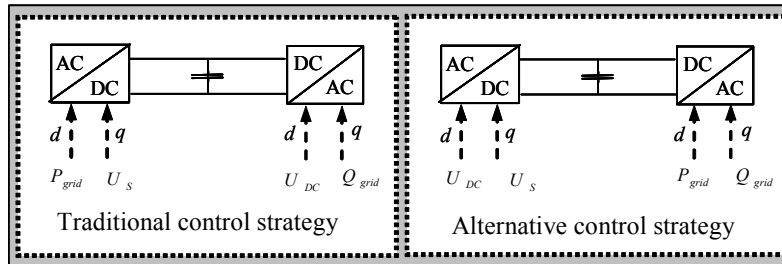


Figure 14: Control strategies.

Notice that in the alternative control strategy, the control functions of each converter are slightly reversed, i.e. the DC-link voltage U_{DC} is controlled by the generator-side converter and not by the grid-side converter as in the traditional control strategy. Meanwhile the active power P_{grid} is controlled by the grid-side converter and not by the generator-side converter. Notice that, such control is only possible if an active rectifier e.g. IGBT converter is used.

In the alternative control strategy, the fault ride-through capability is directly integrated in the control strategy. As the generator-side converter is not directly connected to the grid, it is not affected during grid faults. The DC-link voltage can be therefore kept constant by means of the generator-side converter control. Meanwhile, as the grid-side converter is directly affected by a grid fault, it can transfer less power to the grid than in normal operation conditions. As a consequence, the generator-side converter control reduces the power flow to the DC-link, in order to keep constant the DC-link voltage. This implies automatically a reduction in the generator power as well. Notice that the power imbalance, otherwise present in the DC-link in the case of traditional control strategy, is transferred in this case to the generator. The power imbalance is thus reflected in the acceleration of the generator, which in critical situations is directly

counteracted by the pitch controller. Otherwise, the power surplus is buffered in rotational energy of the large rotating masses.

The conclusion is thus that, the simple reversal of the converter's functions in the alternative control strategy compared to the traditional one makes possible for the considered PMSG wind turbine concept to ride-through during grid faults, without any additional measures.

Nevertheless, in order to enhance even further the fault ride-through capability of this wind turbine concept, a chopper module can be used in the DC-link. The chopper includes a resistance and a power electronic switch, placed in parallel to the capacitor in the DC-link. When the DC-link voltage increases over a critical value, the chopper is triggered and the surplus power is consumed in the chopper resistance.

The following set of simulations illustrates firstly how the full-scale converter multipole PMSG wind turbine equipped with the alternative control strategy is able to ride-through grid faults without any additional measure. Secondly, it is shown how the use of a chopper can enhance the turbine of fault-ride through capability even further, by reducing the amplitude of the oscillations in the shaft torque and thus the mechanical stress of the drive train during grid faults.

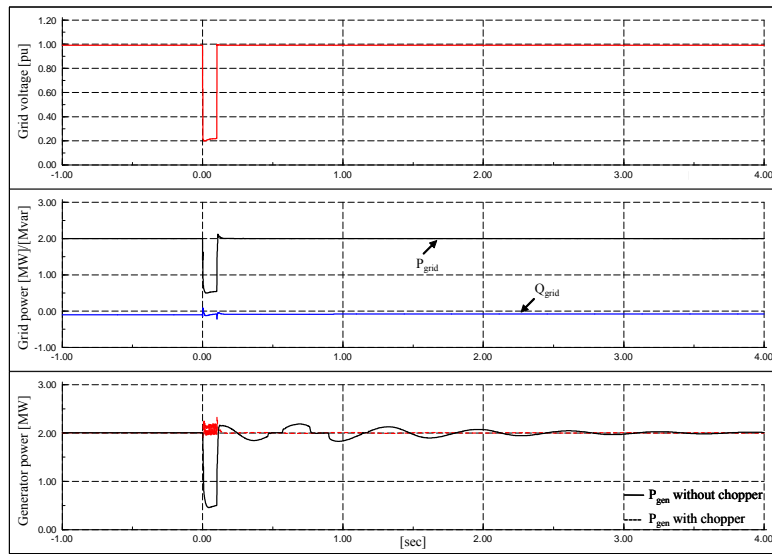


Figure 15: Fault ride-through capability of full-scale converter multipole PMSG wind turbine equipped with the alternative control strategy.

A 100ms three phase short circuit is considered to occur at the high voltage terminal of the 2-windings transformer of the PMSG wind turbine, illustrated in Figure 11. It is assumed that, at the fault instant, the wind turbine works at its rated power first without any chopper attached. As illustrated in Figure 15, the voltage drop occurs at the grid fault instant. Due to this drop, the grid -side converter can transfer only a reduced amount of active power P_{grid} to the grid during the fault. However, it is able to continue to control the reactive power to its reference value provided by the voltage controller. Meanwhile, when no chopper is used, the generator-side converter has to reduce the generator power, in order to be able to keep the DC-voltage constant. This action leads to a power imbalance between the reduced generator power and the unchanged aerodynamic turbine power. As result, the generator starts to accelerate and the drive train gets untwisted and starts to oscillate, as illustrated in Figure 16. Notice that, the oscillations in the drive train are visible in both the generator speed and the shaft torque. They are however quickly damped by the damping controller.

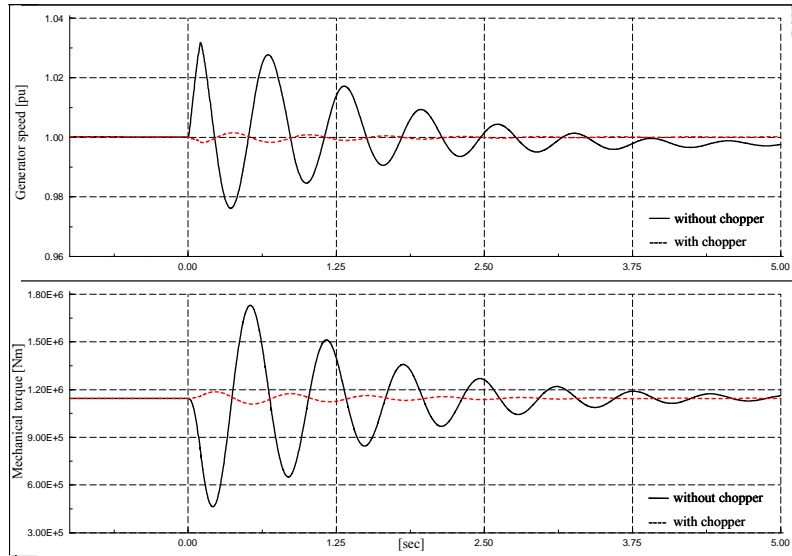


Figure 16: Grid fault impact on the generator speed and on the shaft torque with and without chopper.

The simulations in Figure 15 and Figure 16 illustrate clearly that the wind turbine equipped with the proposed control strategy, is able to ride-through grid faults without any additional measures. The figures show that the use of a chopper during a grid fault can enhance the turbine's fault ride-through capability even further. Notice that, when a chopper is used, the surplus power in the DC link is burned in the chopper and, as shown in Figure 15, it is therefore not necessary to reduce the generator power. Figure 16 shows how the generator acceleration and drive train oscillations are then significantly reduced, when a chopper is used. It is clearly that the chopper reduces effectively the grid fault impact on the wind turbine mechanical stress (smaller oscillations in the shaft torque) and enhances even further the PMSG wind turbines' fault ride-through capability.

The use of a damping controller inside a multi-pole PMSG wind turbine concept is essential for a stable performance both for normal and grid fault operation conditions. The fault-ride through capability of such wind turbine concept equipped with the proposed control strategy is easily facilitated and can be even further enhanced by the presence of a chopper.

5.4 Conclusions

This chapter addresses the dynamic modelling and control issues of three wind turbine concepts:

1. Active stall wind turbine
2. Doubly-fed induction generator (DFIG) wind turbine
3. Multi-pole permanent magnet synchronous generator (PMSG) wind turbine

with special attention directed toward the fault ride-through operation requirement, which asks the turbines to remain connected to the grid even during grid faults.

The performance of the designed fault ride-through control strategy for each individual wind turbine concept has been assessed by means of simulations with the developed models for different operating conditions. These simulations confirm that all the three wind turbine concepts can be controlled to fulfil fault ride-through operations.

It has been shown that the fault ride-through capability of an active stall wind turbine is directly dependent on the ability of the turbine to reduce its mechanical power by pitching quickly the blades during the grid fault.

In the case of variable speed DFIG wind turbines, the fault ride-through capability and grid voltage support are ensured by using a crowbar protection, a damping controller and a proper coordination between frequency converters controllers.

The presence of a damping controller is also crucial for a multi-pole PMSG wind turbine concept, in order to ensure a stable performance for both normal and grid fault

operation conditions. However, in contrast to the DFIG wind turbine, no converter protection is necessary inside multi-pole PMSG wind turbines, their fault-ride through capability being thus easier facilitated. The performed simulations have shown that, by using the proposed alternative control strategy, the fault ride-through capability of this wind turbine concept is directly integrated in the control strategy. This can be even further enhanced by the presence of a chopper, which reduces effectively the grid fault impact on the wind turbine mechanical stress (smaller oscillations in the shaft torque).

The presented dynamic models and control strategies for the three wind turbine concepts constitute important means for the investigation performed during this project in order to assess and better understand the consequences the new grid connection requirements may have on the wind turbine structural loads.

6 Grid requirements impact on wind turbines structural loads

The emphasis in this chapter is on the impact of fault ride-through requirements on wind turbines structural loads during their lifetime. Nowadays, this aspect is a matter of high priority as wind turbines are required more and more to act as active components in the grid, i.e. to stay connected and to support the grid even during grid faults.

6.1 Need for complimentary simulation tools in wind turbine design

The increased penetration of wind power into the power system implies basically that the wind turbines are getting more responsibility in network operation. Their action and complex interaction with the power system have to be therefore analysed carefully by using detailed electrical power system models. On the other hand, the fact that the wind turbines are being designed larger and more flexible than ever before implies larger blade deflections, which require special design and advanced computational aeroelastic models. This is for example the case of the need for detailed calculations for the wind turbines dynamical structural loads caused by grid faults.

Nowadays, the design and the research of wind turbines take place in specific dedicated simulation tools, which are specialised either in the mechanical design area or in the electrical design area regarding grid integration issues of wind turbines. The expertise in these wind turbine design areas is thus built-up independently, with very specific focus and without any influence from one design area to another. In spite of this fact, practical experience shows that there is a considerable interplay between these design areas and this became even stronger in the last years, due to the continuous increasing size of wind turbines. Wind turbine loads are result of a very complex combination of dynamics and excitations both of individual sub-systems (i.e. aerodynamic, mechanic, electric and control) and of the whole entire system, dynamics which are difficult to decouple.

An example for such interference, especially related to large wind turbines, is the risk of the coupling between the generator electrical eigenfrequency and the tower structural frequency, aspect described in details in [21]. It is known that, the low natural frequency of the generators, which is inverse proportional to the generator inertia, decreases with the generator size and it can therefore get closer to the structural frequencies of the wind turbine. A better understanding of such interference between design areas is strongly conditioned by being able to perform a wind turbine design, where the strengths and the knowledge from different specialized design research areas (i.e. mechanical, electrical design and control and grid integration area) can be jointly used, as sketched in Figure 17. By combining the abilities and expertise of complimentary simulation tools, to the extent that it is possible, a detailed insight into the structural as well as the electrical design and control can be thus achieved, and this is very important in the quantification of grid faults' impact on wind turbines' structural loads and lifetime.

In order to cope with the new grid requirements and their impact on wind turbine structural loads, it is also necessary to combine knowledge from complimentary simulation tools, which have expertise in different specialised design areas for wind turbines. Grid faults are typically simulated in dedicated power system simulation tools, based on detailed models for the electrical components of the wind turbine and of the grid, while structural loads of wind turbines are typically assessed in advanced aeroelastic computer codes, which take the flexibility of the tower, blades and other

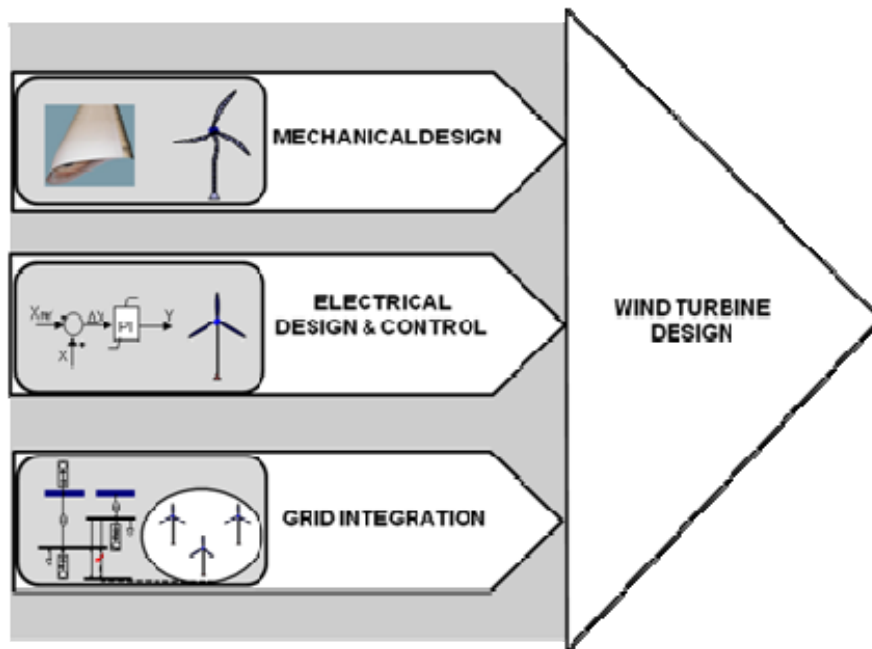


Figure 17: Design areas in the wind turbine design.

structural components of the wind turbines into account.

In this respect, during this project, the interaction between the structural and electrical dynamics of a wind turbine with the dynamic of the grid during grid faults has been studied by using jointly two complimentary simulation tools in a combined simulation approach.

6.2 Computer combined simulation approach

During the project, a combined simulation approach between two complimentary simulations tools has been implemented and assessed for a fixed speed active stall wind turbine. This procedure is combining sequentially two complimentary simulation tools, DIgSILENT and HAWC2, in an offline approach.

DIgSILENT from *PowerFactory* is a dedicated electrical power system simulation tool, which provides deep insight on the electrical interaction between wind turbines and grid [22]. HAWC2 is an aeroelastic simulation code, developed at Risø-DTU National Laboratory for Sustainable Energy, which provides a deep insight on the aeroelastic and mechanical loads of the wind turbine. It is an advanced model for the flexible structure of the wind turbines, based on a multibody formulation [23]. These and other similar simulation tools are used intensively by the wind energy industry at the moment to verify grid codes compliance of wind turbines.

The detailing level in the modelling of different wind turbine components for the two considered simulation tools is very different. DIgSILENT contains very detailed models for the electrical components of the wind turbine and the grid, and simplified models for the aerodynamic and mechanical parts of the wind turbine. For example in DIgSILENT the mechanical system is represented as a simplified 2 mass-model [8], driven by the aerodynamic torque, determined based on the aerodynamic characteristic corresponding to a certain pitch angle and wind speed, while rotor aerodynamics are represented by a static aerodynamic coefficient curve, as described in Chapter 5. The

simulations in DIgSILENT reflect thus details on the electrical interaction between the wind turbine and the grid, but not on the wind turbine structural loads. On the other hand, HAWC2, as it takes the flexibility of the tower, blades and other components of the wind turbines into account, it contains very detailed models for the aeroelastic and mechanical aspects in a wind turbine. The modelling of electrical components and control of a wind turbine in aeroelastic code HAWC2 consists of an external DLL interface, and no grid dynamics are included. If electrical component models have to be considered inside aeroelastic codes, they are typically very simplified [24].

The idea of the proposed simulation approach is to jointly assess both the electrical and the structural design aspects of the wind turbine during grid faults, by coupling to tools consequently. The wind turbine electrical interaction with the grid during grid faults is thus assessed in DIgSILENT, while the wind turbine loads caused by grid faults are simulated and analysed in HAWC2. The chain of the joint simulation approach starts from the power system due to the grid fault simulated in DIgSILENT. As illustrated in Figure 18, the generator stator voltage and the pitch angle simulated in DIgSILENT are used as interface signals, i.e. as inputs to the wind turbine model in HAWC2, in order to simulate and analyzed thus the structural loads caused by the grid fault.

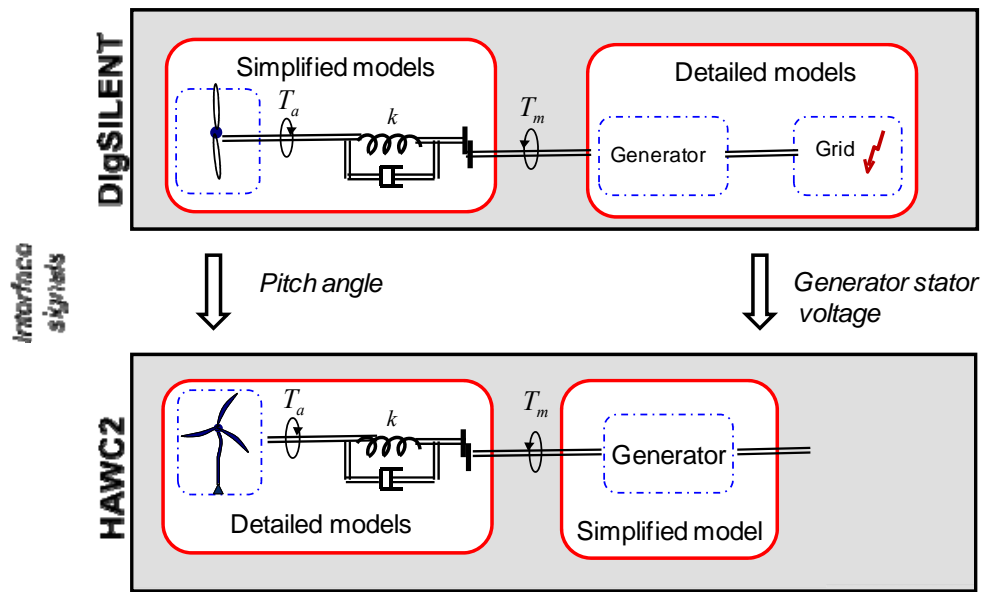


Figure 18: Wind turbine models in DIgSILENT and HAWC2 and their interface signals.

Notice that the key to access a successful combination of these two complimentary simulation tools is strongly dependent on a proper definition of the interface signal between them. During the project, it has been experienced, that especially for wind turbines with directly connected squirrel-cage induction generators, it is not sufficient to use the electromagnetic generator torque, as interface signal between DIgSILENT and HAWC2, as there does not exist any close loop between the generator torque and the generator speed [26-27]. In order to overcome this, a simplified generator model has to be implemented inside the HAWC2 environment. This model is written in a state space form only in terms of the rotor fluxes in dq synchronous reference frame [17], i.e. the electric transients of the stator are neglected.

The decision of which interface signal should be used between the complimentary simulation tools has been therefore demonstrated to be of primary importance in the assessment of the fault ride-through operation impact on the wind turbine structural loads.

6.3 Case study

In the following, a case study is presented to emphasize the proposed computer combined simulation procedure and thus to reflect both the electrical and the structural

response of an active stall wind turbine during grid faults. A simplified simulation scenario of a short circuit in a reduced wind power installation is performed and presented together with a rainflow analysis of the structural loads. The rainflow analysis is accomplished for two cases, one where the turbine is immediately disconnected from the grid when a grid fault occurs and one where the turbine is equipped with a fault ride-through controller and therefore it is able to remain connected to the grid during the grid fault.

Notice that the quantitative results of this investigation are not necessarily representative for other wind turbines of the same type, since they depend critically on the drive train torsional characteristics, as well as on the generator parameters. They are neither representative for variable speed wind turbines, where the presence of frequency converter can imply different behaviour and protection issues. Moreover, the variable speed wind turbines where the generator is connected to the grid through a full-scale converter may be relatively immune to grid faults from a structural point of view.

Simulation setup

The simulation setup is sketched in Figure 19. A fixed speed 2MW active stall wind turbine, equipped with a squirrel-cage induction generator is connected to a typical-medium voltage (MV) distribution network through a step-up transformer.

The dynamic model of the active stall wind turbine and its control strategy designed for fault-ride through operation are implemented inside DIgSILENT, according to the description done in Chapter 5.



Figure 19: Grid model and interface signals between DIgSILENT and HAWC2 for the case of an active stall wind turbine.

The grid model is represented by a Thevenin equivalent, consisting of a constant magnitude/frequency voltage source and a serial impedance. Such representation is typically used, when no specific grid is in focus and generalised conclusions are sought. Grid faults may occur at any point in the system. However, in this study, a 3 phase short circuit on 10kV busbar, with duration 100ms, is simulated in DIgSILENT by using the RMS (electromechanical transient models) simulation feature for longer-term dynamics. [27] confirms that the wind turbine mechanical torque shaft during grid faults is predicted in DIgSILENT in the same way no matter whether a detailed electromagnetic transients models (EMT) or a reduced RMS generator model, i.e. neglecting the stator transients, is used.

In order to assess the maximum wind turbine structural stresses developed during grid faults, the worst scenario is simulated, i.e. it is assumed that the wind turbine operates at rated power and that the fault is closest to the wind turbine and has a minimum fault impedance.

Besides the simulation layout, Figure 19 sketches also the offline combined simulation approach between DIgSILENT and HAWC2. Notice that the DIgSILENT simulation is performed first with main focus on the electrical interconnection between the wind turbine and the grid during the grid fault. Once DIgSILENT simulation is finished, the generated time series for the generator voltage and the pitch angle, i.e. the interface signals between DIgSILENT and HAWC2, are further transferred to the HAWC2 model. With these signals from DIgSILENT as inputs, the HAWC2 simulation is then performed in order to achieve information about the structural behaviour of the wind turbine during the grid fault.

Simulation results and rainflow analysis of loads

In order to quantify how the grid faults and grid code fulfilment affect the active stall wind turbine structural loads, an analysis of the fatigue and ultimate loads in the lifetime of the wind turbine is performed using the rainflow method. An informative note on this method is given in Annex G of the Wind turbine design requirements standard [6].

In the present analysis, the design load cases are considered according to the design load cases described in the IEC standard [6]. This standard includes a comprehensive list of design situations for fatigue and ultimate load analysis. The load cases selected for the analysis regarding fault ride through are as follows:

- Power production with normal wind conditions (i.e. load case DLC1.2 in [6])
 - For each wind speed between cut-in and cut-out, six 10-minute simulations with different turbulence seed are performed.
- Power production with normal wind conditions plus fault occurrence (i.e. load case DLC2.4 in [6]) – For each wind speed between cut-in and cut-out, twelve 10-minutes simulations with different turbulence seed are performed.

In this case study, for each load situation, 10-minutes simulations are performed from 6m/s to 24m/s with a 2m/s step. A normal turbulence model (NTM) is used according to [6]. A 20 years lifetime is assumed and the probability of each wind speed is calculated based on the Weibull distribution. The turbulence intensity is for a Class A turbine (high turbulence) [6]. The case for power production with normal conditions is referred in the following as **Case0**.

For the power production with fault occurrence situation, it is assumed that the fault occurs half-way through the simulation time. Moreover, a number of 50 fault occurrences during 20 years is considered to be realistic [28]. This amounts to 8.3 hours of fault sequences included in the load calculations.

The present fatigue analysis for the load situation with power production with fault occurrence, considers the following two cases:

Case1: Emergency stop - the wind turbine is immediately disconnected from the grid when a grid fault occurs. The turbine is stopped by ramping the pitch angle to minus 90 degrees. The ramp slope is dictated by the pitch servo speed, which in this work is considered to be 10 deg/sec (maximum pitching rate).

Case2: Fault ride-through - the wind turbine is equipped with a fault ride-through controller, as described in Chapter 5, and it is therefore able to remain connected to the grid even during grid faults. In this case study it is assumed that when the voltage magnitude drops below i.e. 0.7 p.u. for a longer time than 50ms, the active stall control is ordered to reduce the mechanical power of the rotor to 20% of the rated mechanical power. Moreover when the fault is cleared, it is assumed that the turbine continues to be in operation with reduced mechanical power for 5 sec, and then starts ramping up the mechanical power of the rotor. A similar technical solution for fault ride-through control for active stall wind turbines is applied at the Danish offshore wind farm at Nysted constructed in year 2003 [29].

The generator torque and the interface signals between DIgSILENT and HAWC2 for Case 1 and Case 2 are illustrated in Figure 20.

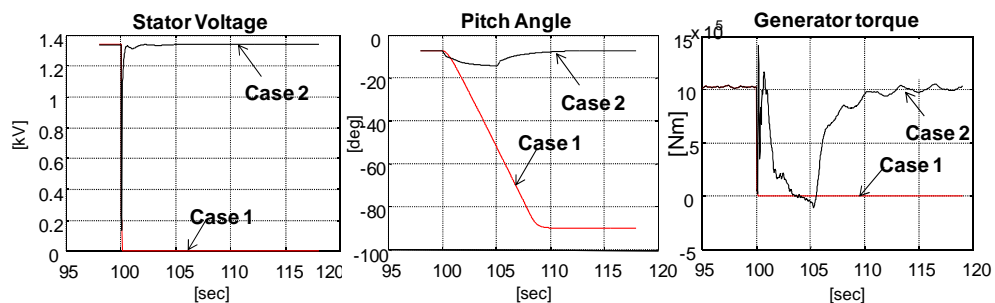


Figure 20: Interface signals (stator voltage and pitch angle) and generator torque during CASE1 (emergency stop) and CASE2 (fault ride-through).

Notice that, due to the grid fault, while in Case1 the generator voltage drops to zero right after the grid fault and remain there as result of the wind turbine disconnection from the grid, in Case2 the generator voltage drops to about 80% of the nominal voltage (less than 20% retained voltage) and recovers to its initial value when the fault is cleared after 100msec. The pitch angle in Case 1 is ramped down to -90 degrees, while in Case2, during and after the fault, the pitch angle corresponds to the predefined reduced setpoint of the aerodynamic power. As soon as the fault is detected, the normal operation controller is thus switched off and replaced by a fault ride-through look- up table containing the pitch angle function of wind speed. When the grid fault is cleared, the pitch angle continues to stay at the fault ride-through look-up table pitch value for a few more seconds, after which it starts to ramp up and reaches its initial normal operation value.

Table 2: Ratio of the equivalent loads for the blade, tower and shaft of the turbine for Case2/Case0 and Case 2/Case1.

Equiv. load ranges for N=10E7		
Load sensor (1Hz eq. load)	Case 2/Case0	Case2/Case1
Blade flap moment, m=12	1.00	0.78
Blade edge moment, m=12	1.00	1.00
Tower top tilt moment, m=6	1.00	1.00
Tower top yaw moment, m=6	1.00	1.00
Tower bottom tilt moment, m=6	1.00	1.00
Tower bottom side moment, m=6	1.00	1.00
Shaft bending moment	1.00	1.00

In order to assess the impact of the fault ride-through requirement on the turbines structural loads, a rainflow analysis for different fatigue measures has been performed. Table 2 illustrates the results of this analysis, by providing the ratio of the equivalent loads for the blade, tower and shaft of the turbine for two comparisons:

- Case2/Case0 – compares the case of power production with normal wind conditions Case0 and the case of power production with fault occurrence and fault ride-through capability Case2.
- Case2/Case1 - compares the case of power production with fault occurrence with emergency stop Case1 and the case of power production with fault occurrence and fault ride-through capability Case2.

Both comparisons are performed for an assumed fault occurrence of 50 in a 20 year lifetime. Similar results have been also obtained for an assumed fault occurrence of 500 and 3000 in 20 years. The latter case was investigated based on feedback from developers in India, for whom such a high occurrence of grid faults is to be expected.

The following remarks are concluded:

- Comparison Case2/Case0 shows that the fault ride-through (FRT) capability does not increase the fatigue measures on the turbine when added to the normal operation case.
- Comparison Case2/Case1 shows that fault ride-through (FRT) capability does not change the fatigue measures on the turbine compared to the traditional emergency stop, except for the flap loads, in which Case2 shows a 22% reduction compared to Case1. The blade flap load reduction in Case2 is most likely due to the excessive speed overshoot of the emergency stop strategy used in HAWC2 simulations. As shown in Figure 20, an emergency shut-down strategy (Case 1) implies pitching, as fast as the pitch servo mechanism allows, to -90 degrees for shutdown and idling. However, to be able to run HAWC2 idling in stall, it was necessary to pitch to a positive 90 degrees instead of -90 degrees and therefore to initially increase the aerodynamic torque instead of decreasing it, leading to a high rotational speed overshoot in Case 1, as illustrated in Figure 21. This speed overshoot in Case 1, has an immediate

influence on the blade flap moment and tower fore-aft moment, as illustrated in Figure 22 and Figure 23. Otherwise, the emergency shut-down would not be typically expected to increase the equivalent flap loads, especially due to the low number and duration of fault occurrences compared to the whole lifetime of a wind turbine.

The fatigue load analysis shows thus that for the considered case study, the

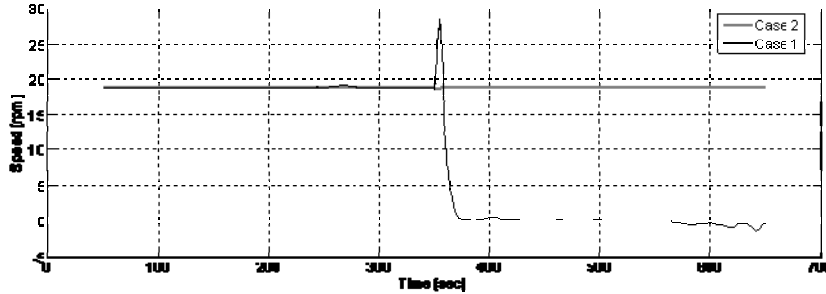


Figure 21: Rotor speed in HAWC2 during CASE1 (emergency stop) and CASE2 (fault ride-through).

fulfilment of the fault ride-through requirement by an active stall wind turbine does not change the fatigue loads for all sensors, in comparison to the traditional emergency stop.

It can be thus concluded that the normal operation is dominant for fatigue loads. Besides the fatigue loads, the ultimate loads for the case of a fault ride-through has been also investigated, based on the following cases defined in the IEC standard [6]:

- Power production with normal wind conditions (*i.e. load case DLC1.1 in [6]*)
- Power production with extreme turbulence model (*i.e. load case DLC1.3 in [6]*)
- Power production with normal wind conditions plus occurrence of fault (*i.e. load case DLC2.1 in [6]*)

As in the fatigue analysis, in the ultimate analysis 10-minutes simulations are performed from 6m/s to 24m/s with a 2m/s step for each load situation, six simulations with different turbulence seed for power production with no fault, and twelve in the case

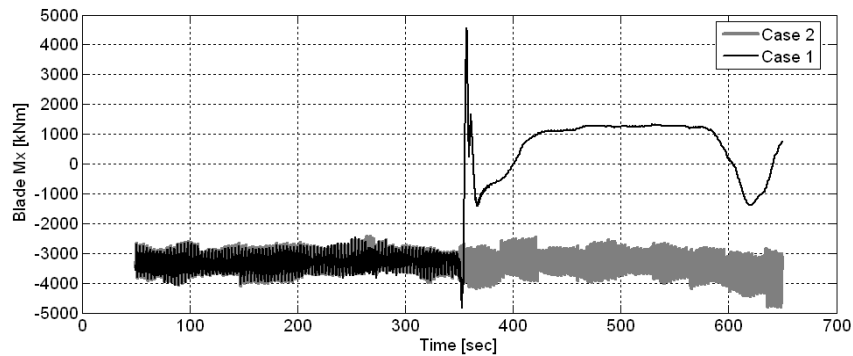


Figure 22: Blade flap moment in HAWC2 during CASE1 (emergency stop) and CASE2 (fault ride-through).

with fault. A statistical analysis is performed, and the maximum absolute value for each simulation is used as a measure of the ultimate load. Figure 24 illustrates, for example, the mean, maximum, minimum and standard deviation values for the blade flap moment. Notice that the maximum of the absolute value of the maximum and minimum moment gives the ultimate load, which in this case is for DLC1.3, power production with extreme turbulence, at 24m/s.

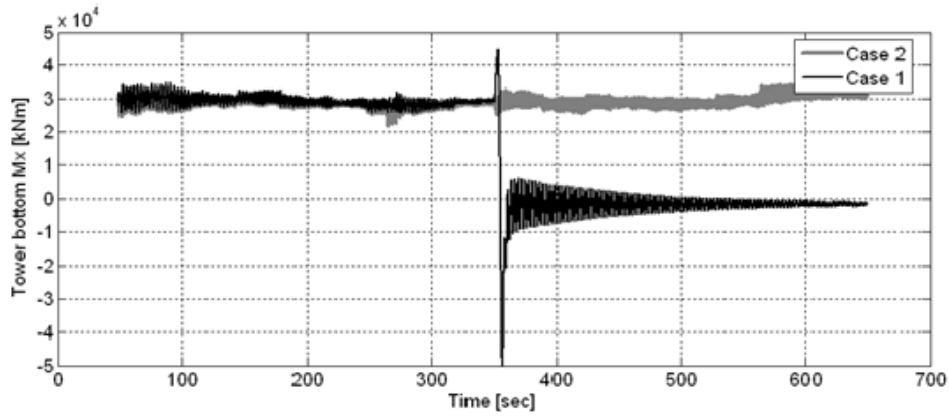


Figure 23: Tower bottom moment during CASE1 (emergency stop) and CASE2 (fault ride-through).

The result of the ultimate load analysis is that the fulfilment of the fault ride-through requirements by an active stall wind turbine, does not have the maximum effect on the loads of the wind turbine components (blade flap moment, blade edge moment, tower top tilt moment, tower top yaw moment, tower bottom tilt moment, tower bottom side moment, shaft bending moment) compared to the situation of power production with extreme turbulence model (DLC1.3).

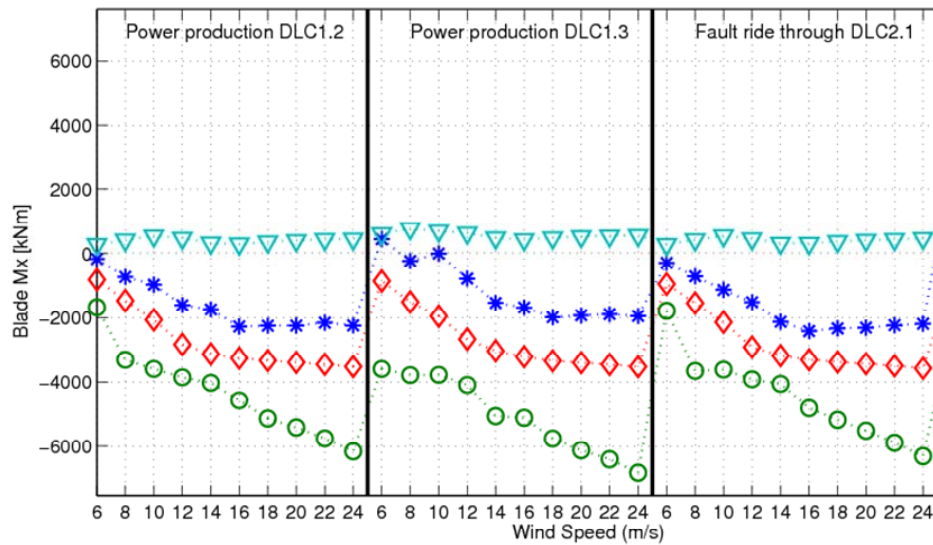


Figure 24: Maximum (*), minimum(\circ), average(\diamond) and standard deviation(\blacktriangledown) of the blade flap moment for one random seed.

6.4 Conclusions

This chapter is mainly focusing on the impact of the fault ride-through requirements on the wind turbine structural loads and on the need for an integrated wind turbine design with simultaneous focus on both structural and electrical design aspects.

In this respect, a computer combined simulation approach for the quantification of wind turbines structural loads, caused by the fault ride-through grid requirement, has been proposed and exemplified for a case study of an active stall wind turbine and a 100ms three phase short circuit fault on the grid. The investigation has in particular been focused on the analysis of structural loads on tower and blades.

In order to quantify how the grid faults and grid codes fulfilment do affect the wind turbine loads and thus its lifetime, a rainflow analysis of the structural loads has been

performed and compared for two cases, i.e. one when the turbine is immediately disconnected from the grid when a grid fault occurs and one when the turbine, as it is equipped with a fault ride-through controller, remains connected to the grid during the grid fault. A rainflow and a statistical analysis for fatigue and ultimate loads, respectively, have been accomplished.

The investigations performed during the project have shown that, for the specific case study of an active stall wind turbine, neither the fatigue nor the ultimate structural loads on the tower and the blades of a turbine are affected by the fulfilment of the fault ride-through requirement. The quantitative results of the investigations are not necessarily representative for other wind turbines of the same type, since they depend critically on the drive train torsional characteristics, as well as on the generator parameters. They are neither representative for variable speed wind turbines, where the presence of frequency converter can imply different behaviour and protection issues. In the authors' opinion, as the generator of variable speed wind turbines is connected to the grid through a full-scale converter, these turbines may be even more immune to grid faults and thus even less affected from a structural point of view.

7 Wind turbines storm control strategies – operation over 25m/s

This chapter presents the investigations performed during the project regarding the design of control strategies, which enable variable speed wind turbines to operate in storm conditions, i.e. at wind speeds higher than 25m/s, without a substantial increase in the structural loads.

Due to high penetration of wind energy into the electricity grid, there is a keen interest from the grid companies to ensure a reliable and robust energy production in storm situations, even if the turbine is not running at rated power output. To the best of our knowledge, work on incurring loads from storm reduction control strategies has not been published yet. This is also the case for Enercon, which has implemented, but not published its own storm control strategy.

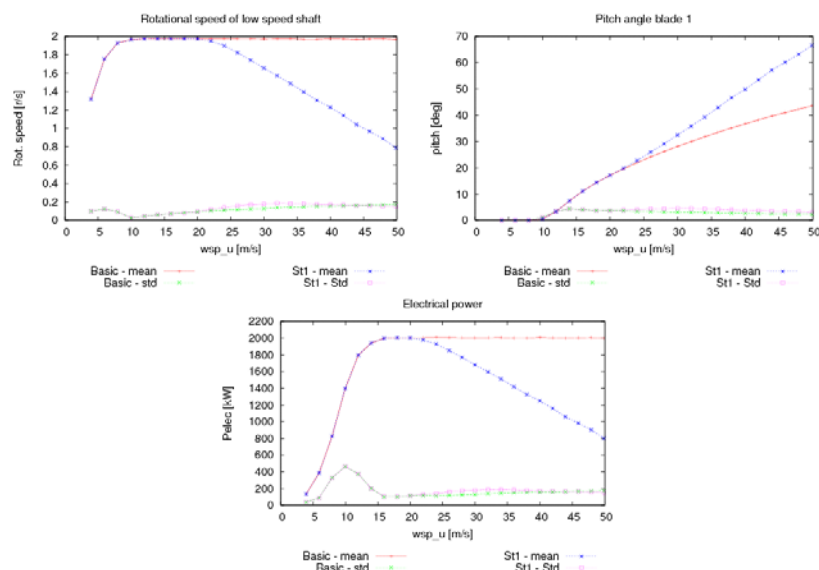
The chapter is also presenting a set of load cases for wind speeds from 4m/s to 50m/s with turbulence intensities according to IEC61400-1 rev 3 class IA [6], which has been performed in the Risø-DTU non-linear wind turbine simulation tool HAWC2 [23]. A class IA turbine i.e. high turbulence site and high average wind speed, has been selected as the worst case scenario. Statistics in terms of mean value and standard deviation and rainflow calculations are performed to estimate the impact over the lifetime of the turbine.

7.1 Design of storm controllers

The following controllers and improvements have been investigated and compared:

- **Power-speed controller up to 25m/s (Basic)** – used to operate the turbine up to 25m/s and idling in the higher winds. This is the nominal case used as the base case in the load comparisons.
- **Power-speed controller up to 50m/s (Basic_50)** - the same power-speed controller that typically is used to operate the turbine up to 25m/s, is used now to operate the turbine up to 50m/s. The rated torque and the rotor speed set points are kept the same as in the basic case.
- **Storm Controller (St1)** - the power and rotor speed set-points at high wind speeds are reduced from their nominal values at 25m/s to about half the nominal values at 50m/s. The following two additional dampers (load reduction controllers) have been further implemented in order to reduce the tower loads during storm:
 - **Fore-aft tower damper (ATD)** – an algorithm used for increasing the fore-aft tower damping and for reducing thus the fore-aft tower load. It is using collective pitch based on measurements of the fore-aft tower top acceleration signal;

-



strategy reaches very high values, i.e. up to 60-70 degrees above 45m/s, in order to limit the aerodynamic forces.

Load reduction controllers

The proposed storm controller limits the rotor loads, but not the tower vibration loads (fore-aft and side-to-side), which are still increasing. The reason is that, the very high pitch angle values, needed in the storm control strategy to limit the aerodynamic forces, lead unfortunately to a reduced aerodynamic damping and therefore to high tower vibrations. Two additional load reduction controllers have been therefore implemented in the storm controller in order to increase the aerodynamic damping.

The load reduction controllers consist mainly of two active tower dampers, one for increasing the fore-aft tower damping Figure 27(a) and one for increasing the side-to-side tower damping Figure 27(b).

The fore-aft tower damper contributes with a correction of the pitch angle coming from the PI pitch controller, i.e. a collective pitch angle $\Delta\theta$ correction is added to the power speed collective pitch (Pitch Ref). The pitch correction is the result of a band-pass filtered measurement of the fore-aft tower top acceleration signal tow_acc_y , multiplied by a proportional gain.

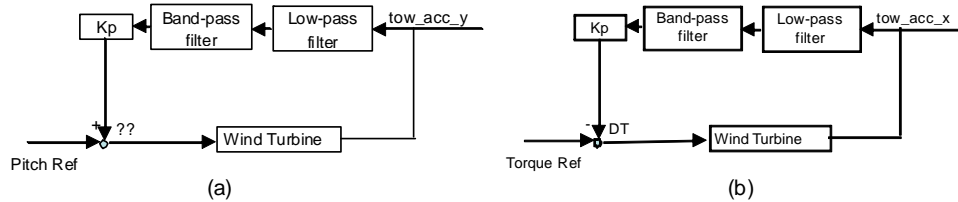


Figure 27: Control strategy for the fore-aft tower damper (ATD) and for the side-to-side tower damper (LTD).

In a very similar manner, in order to increase the lateral tower damping, the band-pass filtered sideward tower top acceleration tow_acc_y , multiplied by a proportional gain, is added as an additional torque reference signal DT to the existing torque reference signal from the existing power-speed regulator (Torque Ref). The design and tuning of the controllers are presented in details in [31].

7.2 Comparison of results

A set of power production load cases ranging from wind speeds of 4m/s to 50m/s with turbulence intensities according to IEC61400-1 rev 3 class IA has been simulated.

Statistical overview

Statistics in terms of mean value and standard deviation of the simulated time-series are used to have an indication on the increase of loading on different wind turbine components. In order to ensure the loads within a reasonable range, the mean value and the standard deviation should be similar or lower than that at the normal cut-out wind speed of 25m/s.

Firstly the load reductions achieved by using the storm controller instead of the basic controller at higher wind speeds than 25m/s have been investigated. Figure 28 and Figure 29 illustrate the mean and the standard deviations values for the blade, shaft moments and tower moments respectively, for the Basic_50 control strategy and for the storm control strategy St1. Notice that Basic_50 controller results in increasing loads on all major load components at wind speeds the higher than 25m/s. By using the storm controller, it is possible to keep producing power at very high wind speeds and still to limit the rotor loads and the shaft loads to the normal operation loads at 25m/s. However, this is not the case for the tower loads, which are still significantly increasing though the storm controller is used.

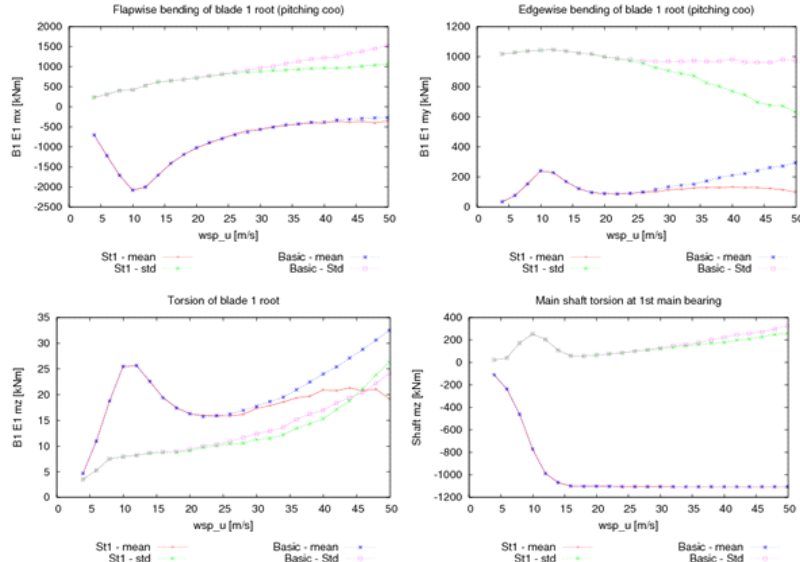


Figure 28: Comparison of mean values and standard deviation of the blade root moments (flapwise, edgewise) and shaft moments for the storm control strategy (St1) and the nominal power-speed control strategy (Basic_50).

Special focus on the tower vibrations, both fore-aft and side-to-side, when the turbine is running with storm controller at wind speeds up to 50m/s, is therefore still very important.

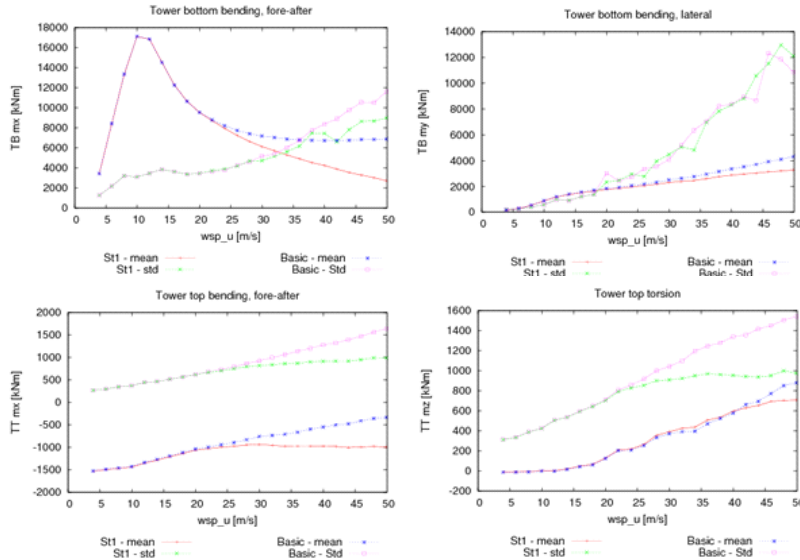


Figure 29: Comparison of mean values and standard deviation of the tower bottom and tower top moments (fore-aft, lateral) for the storm control strategy (st1) and the nominal power-speed control strategy (Basic_50).

The reason for this increase in tower loads, in combination with high load input from the high wind speeds, is the reduced aerodynamic damping as a direct consequence of the very high pitch angles. The turbine has to operate at pitch angles up to 60-70 degrees at 50m/s in order to limit the aerodynamic forces.

The effect of the two tower load reduction controllers for wind speeds from 4m/s to 50m/s are looked at. Figure 30 illustrates, for example, the mean and the standard deviations values the tower bottom fore-aft bending moment and the pitch angle (actuator) of the simulated time-series of the storm control strategy with and without the fore-aft tower damper controller. Notice that the fore-aft tower damper reduces the standard deviations of the tower bottom fore-aft bending moment in wind speeds from

20m/s and above. The highest reduction is above 35m/s. It is worth noting that the duty on the pitch system with the additional collective pitch angle contribution from the fore-

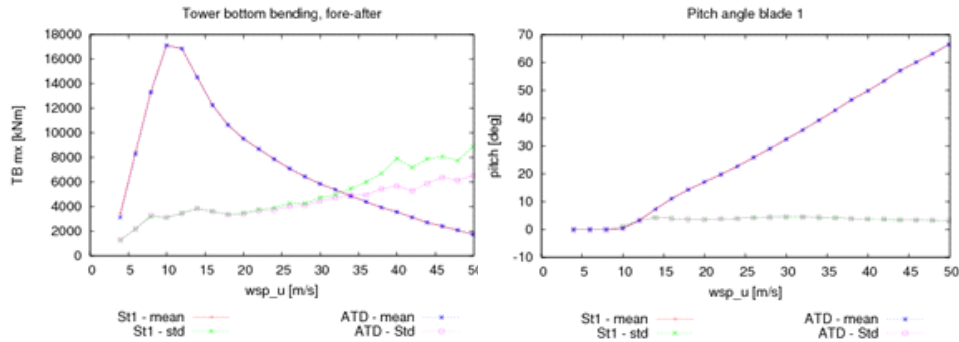


Figure 30: Comparison of mean values and standard deviation of the tower bottom fore-aft moment and the actuator response (pitch angle) for the storm control strategy (st1) and the fore-aft tower damper (ATD).

aft tower damper is negligible.

Figure 31 illustrates the mean and the standard deviations values of the tower bottom lateral bending moment and the shaft torque value of the simulated time-series of the storm control strategy with and without the additional lateral tower damper. Notice that, the lateral tower damper results in a reduction of the standard deviation of the side-to-side tower moment at almost all wind speeds, with no changes in its mean value. The penalty is a small increase in the shaft moment's standard deviation at the higher wind speeds above 40m/s.

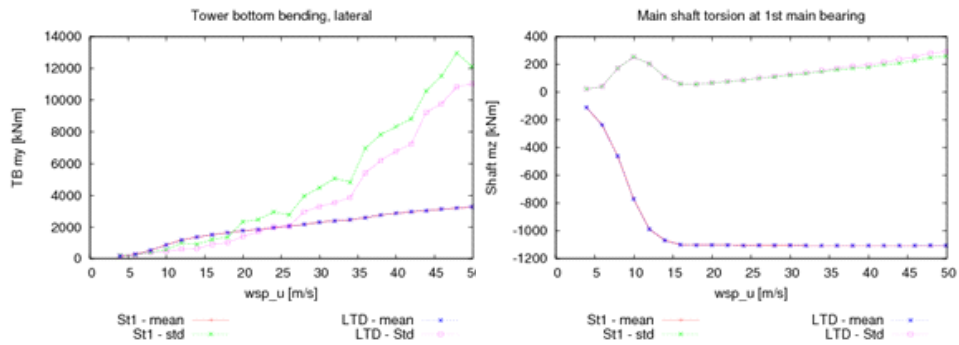


Figure 31: Comparison of mean values and standard deviation of the tower bottom lateral moment and actuator response (shaft moment) for the storm control strategy (st1) and lateral tower damper (LTD).

Fatigue measures

To quantify the increase in fatigue loads, a fatigue analysis has been performed for all the considered controllers and the 1Hz equivalent loads have been compared to the nominal case, i.e. operating up to 25m/s and idling in the higher winds (Basic).

It should be noted that a ‘worst-case’ scenario has been chosen in terms of selected site type (Class IA). The Weibull distribution will bias to the lower wind speed ranges in Class II and Class III turbines ($V_{ave}=10, 8.5, 7.5$ respectively for the three wind classes).

The following design load situations as defined in the IEC61400-1 rev 3 standard for fatigue analysis have been considered:

- Power production from cut-in to cut-out wind speeds (DLC 1.2)
- Parked (standing still or idling) up to $0.7 \cdot V_{ref}$: modified to idle up to 50m/s (DLC 6.1)
- Start-up and shut-down (DLC 3.1 and DLC 4.1)

The fatigue analysis has been described in details in [31]. In order to assess the impact of start-ups and shut-downs when operating in the higher winds, these have also been included in the fatigue analysis for three cases: the ‘nominal’ case i.e. operating up

to 25m/s and operating up to 50m/s with and without the storm controller active. Start-up and shut-down has not been included in the case of the load reduction controllers, as in these design cases the load reduction controllers are not active, and thus start-up and shut-down will be as for the power-speed controllers. A number of 1000 occurrences of both start-up and shut-down are included. Each simulation is 200 seconds resulting in 57h of each start-up and shut-down over the turbine lifetime. Results are presented with and without start-up and shut-down, as indicated in the caption of Table 3.

A rainflow count has been performed, for both the basic and storm controller running up to 50m/s, referred to as 'Basic_50' and 'St1', respectively. In Table 3 the 1Hz equivalent loads are compared to the nominal case i.e. operating up to 25m/s with the basic controller and then idling up to 50m/s. The main results shown do not include start-up and shut-down. With start-up and shut-down the blade flap moment ratio changes (the ratio in bold/brackets). The following remarks have been done:

- The contribution from operation in the higher winds is not very high for the blade and tower top loads, especially with the storm controller active (St1). In this case the increase in flap loads is only 2%, and 4% and 2% for the yaw and tilt loads respectively.
- The tower fore-aft loads are increased by 5% and the side-to-side loads are actually decreased by 18% as the generator operation in higher winds seems to act as a damper to the tower side-to-side loads.
- The fact that the fatigue loads are not substantially increased is due to the fact that the turbine is not operating at these higher wind speeds for a substantial amount of time, even though the worst case scenario from the IEC61400-1 rev 3 has been selected for this study, i.e. a Class I wind turbine. In fact not even 1 hour in total in a lifetime of 20 years is spent above 40m/s.
- Start-up and shut-down flap loads are higher when idling in the higher winds than if operating.

Table 3: Equivalent loads of the basic and storm controller when running up to 50m/s, as compared to those when running up to 25m/s. The ratio in the brackets are with start-up and shut-down included.

Equiv. load ranges for N=10E7		
Load sensor (1Hz eq. load)	Basic_50	St1
Blade flap moment, m=12	1.07 / [1.04]	1.02 / [1.00]
Blade edge moment, m=12	1.00	1.00
Tower top tilt moment, m=6	1.05	1.02
Tower top yaw moment, m=6	1.06	1.04
Tower bottom fore-aft moment, m=6	1.05	1.05
Tower bottom lateral moment, m=6	0.84	0.82
Shaft bending moment	1.01	1.01

A rainflow has been also performed for the case when in the storm control strategy the load reduction controllers have been implemented. The 1Hz equivalent loads have been again calculated and compared to the nominal case Basic_25 and idling up to 50m/s. Notice that the operation in storm situations does not increase the fatigue loads, and is actually favorable for the tower side-to-side loads. For completeness, the results for the fore-aft tower damper (ATD) and the side-to-side tower damper are shown in Table 4 with the basic controller 50m/s (Basic_50) and the storm controller (St1). The following observations have been made:

- When running up to 50m/s with no load reduction controllers implemented the increase in fatigue loads is not prohibitively high:
 - The blade flap loads are increased by 7%, the tower top loads by 5-6%.
 - The effect of operating is actually favorable for the tower side-to-side loads, compared to idling, due to damping provided by the generator torque.
- The fore-aft tower damper reduces the blade flap loads to 94% of the nominal case and the tower bottom fore-aft loads from 5% (Basic_50) above to 2% above the nominal case.
- The lateral tower damper reduces even further the lateral tower loads to 61% of the nominal case, with no increase in the shaft loading.

The presented load reduction control strategies do not compete with each other: the LTD acts on the generator torque, while ATD acts on the pitch angle. It is expected that, the load reductions achieved by implementing these independently in HAWC2 would be the same, if running these controllers at the same time. The only loads that have not been reduced to the value of or below that of the nominal case are the tower top loads and the tower bottom fore-aft. Compared to the nominal case they are 2% higher.

Table 4: Equivalent loads of the load reduction controllers when running up to 50m/s, as compared to those when running up to 25m/s + idling.

Equiv. load ranges for N=10E7				
Load sensor (1Hz eq. load)	Basic_50	St1	ATD	LTD
Blade flap moment, m=12	1.07	1.02	0.94	1.01
Blade edge moment, m=12	1.00	1.00	1.00	1.00
Tower top tilt moment, m=6	1.05	1.02	1.02	1.01
Tower top yaw moment, m=6	1.06	1.04	1.03	1.02
Tower bottom fore-aft moment, m=6	1.05	1.05	1.02	1.04
Tower bottom lateral moment, m=6	0.84	0.82	0.83	0.61
Shaft bending moment	1.01	1.01	1.01	1.00

Extreme loads

An indication of the ultimate loads on the turbine is given from the maximum values of the load cases performed for the fatigue analysis.

The ratio of the maximum values for all the implemented controllers divided by the maximum values from the nominal case is presented in Table 5. For a complete analysis of the extreme loads on the turbine an ultimate strength analysis according to [6] would need to be performed and additional design load cases of power production with the occurrence of a fault could contribute to the ultimate loading of the turbine (DLC 2.2 and DLC 2.3).

Notice that, in contrast to the fatigue loads, the ultimate loads are higher when running up to 50m/s (Table 5), specifically for the tower-top and the shaft moments. By looking at the best resulting load reduction, provided by the all load reduction controllers, as it can be assumed that all the controllers are active simultaneously and result in the same load reductions, the maximum loads on the turbine:

- for the blade moments increases by 5%-7%.
- for the tower bottom fore-aft increases by 4% increase, while for the tower bottom side-to-side decreases by 5%.
- for the tower top moments, both tilt and yaw, increases by 35%.
- for shaft bending moment increases by 54%.

Table 5: : Ratio of maximum values from implemented controllers divided by the maximum values of the nominal case i.e. basic controller running to 25m/s and idling thereafter.

Load sensor	Basic_50	St1	ATD	LTD
Blade flap moment	1.58	1.29	1.07	1.29
Blade edge moment	1.62	1.08	1.05	1.08
Tower top tilt moment,	1.92	1.46	1.35	1.47
Tower top yaw moment	2.28	1.58	1.35	1.56
Tower bottom tilt moment	1.86	1.20	1.04	1.17
Tower bottom side moment	0.83	0.82	0.95	0.76
Shaft bending moment	1.63	1.55	1.54	1.58

7.3 Conclusions

The emphasis in this chapter is on storm control strategies, that enable variable speed wind turbines to operate at wind speeds higher than 25m/s, without a substantial increase in the structural loads.

A storm controller is proposed, investigated and compared with the traditional control approach running up to 50m/s. The storm controller is designed in such a way that, the rotor speed and the power set-points are reduced gradually for increasing wind speeds above the cut-out wind speed. As this action implies pitch angle values up to 60-70 degrees to limit the aerodynamic forces, the storm controller succeeds in limiting the rotor loads, but not also the tower loads. Two load reduction controllers are therefore implemented additionally to the storm control strategy in order to decrease the fore-aft and lateral tower loads.

A set of load cases for wind speeds from 4m/s to 50m/s with turbulence intensities according to IEC61400-1 rev 3 class IA has been performed, in order to calculate the increase in fatigue damage when allowing the turbine to run in storm conditions. The loads experienced by the turbine in wind speeds up to 25m/s, including idling up to 50m/s, and operating up to 50m/s are compared with the loads corresponding to the storm control strategy, with and without additional load reduction controllers. Statistical analysis shows that, the increase in fatigue damage, when running up to 50m/s, is not as high as would be expected, and by taking idling in the higher winds into account, the effect of operating is actually favorable for the tower side-to-side loads. The storm control strategy reduces the blade flap loads and the tower top loads, and has a negligible effect on the tower loads. The tower loads are compensated by the additional load reduction controllers, i.e. the fore-aft tower damper reduces the fore-aft tower bottom loads from 5% higher compared to the nominal case to 2% higher than the nominal case, while the side-to-side tower damper reduces the side-to-side loads from 84% compared to the nominal to 61% compared to the nominal.

For the extreme loads analysis the maximum component loads were looked at and it was seen that there is a significant increase in tower top and shaft moments, even with loads controllers included.

8 Conclusions and future work

As conclusions are presented at the end of each individual chapter, some more general conclusions are made in the following.

To the best of authors' knowledge, the work presented in this report constitutes a pioneer step toward better understanding how the wind turbines loads are affected by the consequences of the new grid connection requirements. At the moment only very few publications in the literature deal with this subject, however with no statistical or rainflow load analysis included, as is done in this work. The present investigation has in particular been focused on fault-ride through (FRT) requirements, whose fulfilment specifies the wind turbines to remain connected to the grid even during and after an abnormal grid voltage is detected. FRT requirements have been chosen in this research,

as it is a primordial requirement for wind turbines at the moment, but of course in the future the affect of other requirements can also be relevant to investigate.

The investigation in this work has in particularly been focused on the structural loads on the tower and the blades of wind turbines. In a future work could also be interesting to analyse other loads, i.e. on the drive train of wind turbines.

One should have in mind that the fast development of the wind energy industry implies a continuous revision not only of the grid connection requirements, but also of the certification standards. Together with other experiences, the knowledge assessed during this project can be enhanced and combined in future research projects in order to also update the certification process of wind turbines according to the progress of technology and of the new grid connection requirements.

Another aspect, which has been revealed during this project, is the fact that the future design and research of wind turbines should be based on an integrated design approach, in order to achieve a thorough and immediate insight into the complex interplay between the structural, mechanical and control design issues of a wind turbine. Such an integrated design should be performed based on online combination and communication between simulation tools with strong complementary skills, i.e. for aeroelastic, mechanical, electrical and control design areas.

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